DOCUMENT RESUME

ED 071 899 SE 015 536

TITLE	Project Physics Handbook 4, Light and Electromagnetism.
INSTITUTION	Harvard Univ., Cambridge, Mass. Harvard Project Physics.
SPONS AGENCY	Office of Education (DHEW), Washington, D.C. Bureau of Research.
BUREAU NO	BR-5-1038
PUB DATE	68
CONTRACT	OEC-5-10-058
NOTE	63p.; Authorized Interim Version
EDRS PRICE	MF-$0.65 HC-$3.29
DESCRIPTORS	Electricity; Instructional Materials; Laboratory Experiments; *Laboratory Manuals; Light; *Physics; *Science Activities; *Science Experiments; Secondary Grades; *Secondary School Science
IDENTIFIERS	Harvard Project Physics

ABSTRACT

Seven experiments and 40 activities are presented in this handbook. The experiments are related to Young's experiment, electric forces, forces on currents, electron-beam tubes, and wave modulation and communication. The activities are primarily concerned with aspects of scattered and polarized light, colors, image formation, lenses, cameras, refraction, gratings, speed of light, electric fields, batteries, magnets, perpetual motion machines, electron tubes, Faraday disc dynamo, generators, motors, and Bell telephone science kits. Demonstrations, construction projects, and self-directed instructions are stressed in these activities. The four chapters in the handbook are designed to correspond to the text materials, with complete instructions in each experiment. Some experiments are suggested for assignment, and the remaining are used at student discretion. Illustrations and film loop notes for explanation use are included. The work of Harvard Project Physics has been financially supported by: the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education, and Harvard University. (CC)

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Project Physics **Handbook** 4

An Introduction to Physics

Light and Electromagnetism

ISE 015 536

This handbook is the authorized interim version of one of the many instructional materials being developed by Harvard Project Physics, including text units, laboratory experiments, and teacher guides. Its development has profited from the help of many of the colleagues listed at the front of the text units.

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The work of Harvard Project Physics has been financially supported by the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education and Harvard University.

Consult the Project Physics text for a partial list of the current and recent staff, consultants and advisory committee.

03-073535-1

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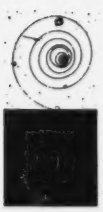
Project Physics **Handbook**

An Introduction to Physics **4** Light and Electromagnetism



Authorized Interim Version 1968-69

Distributed by **Holt, Rinehart and Winston, Inc.** New York Toronto

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This Student Handbook is different from laboratory manuals you may have worked with before. There are far more things described in this handbook than any one student can possibly do. Only a few of the experiments and activities will be assigned. You are encouraged to pick and choose from the rest any of the activities that appear interesting and valuable for you. A number of activities may occur to you that are not described in the handbook and that you would prefer to do instead. You should feel free to pursue these in consultation with your teacher.

There is a section corresponding to each chapter of the text. Most sections are composed of two major subsections—Experiments and Activities.

The Experiments section contains complete instructions for the experiments your class will be doing in the school laboratory. The Activities section contains suggestions for demonstrations, construction projects and other activities you can do by yourself. (The division between Experiments and Activities is not hard and fast; what is done in the school laboratory and what is done by the student on his own may vary from school to school.)

The Film Loop Notes give instructions for the use of the film loops which have been prepared for this course.

EXPERIMENT 32 Young's Experiment – Measuring the Wavelength of Light

You have seen how ripples on a water surface spread out after having passed through an opening (this is called diffraction), and how ripples spreading out from two coherent sources reinforce each other in some places and cancel out in others (this is called interference). Sound and ultrasound behave in a similar way. These diffraction and interference effects are characteristic of all wave motions, and if light has a wave nature it too must show diffraction and interference effects.

At first this may seem unlikely. We all know that "light travels in straight lines;" but if light is diffracted it must mean that light bends around corners. Have you ever noticed light spreading out after passing through an opening, or behind an obstacle? Probably not—so try this simple test: look at a narrow light source several meters away from you (a straight-filament lamp is best, a single fluorescent tube far away will do). Hold two fingers in front of one eye and look at the light through the gap between them. The fingers must be parallel to the light source (Fig. 1.). Now slowly squeeze your fingers together to decrease the width of the gap.

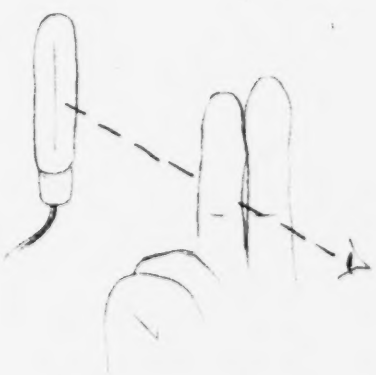


Fig. 1

Q1 What do you see? What happens to the light coming through the gap between your fingers as you reduce the gap to a very narrow slit?

Evidently light can spread out in passing through an opening, but for the effect to be noticeable, the opening must be much smaller than the ones used in the ripple tank, or with sound waves. This suggests that light is a wave, but that it has a much shorter wavelength than the ripples on water, the sound or ultrasound.

Do light waves show interference? Again your immediate answer might be "no." Have you ever seen dark areas formed by the cancellation of light waves from two sources? Probably not. As with diffraction, we must arrange for the sources to be small, and close to each other. Hold up in front of one eye the dark film with two narrow transparent slits, and look through the slits at the narrow light source. The slits must be parallel to the light source. You should see some evidence of interference between the light from the two slits.

Two-slit interference pattern

To examine this interference pattern in more detail, fasten the double slit on the end of the wide cardboard tube. Make sure that the end of the tube is light-tight, except for the two slits, of course. (It helps to cover most of the film with black tape.) Stick a piece of Magic Mending Tape over the end of the narrower tube, and insert this end into the wider tube. Set up your tube at least 1.5 meters away from the narrow light source, as shown in Fig. 2. The slits must be parallel to the light source. Now look at the tape screen. (Don't put your eye up against the end of the tube. Your eye should be about a foot away from it. Focus on the screen.) What you see on the screen is

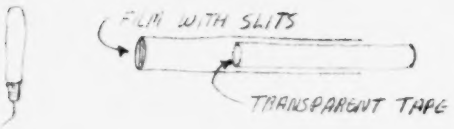


Fig. 2

the interference pattern formed by light from the two slits.

Q2 Describe how the pattern changes as you move the tape further away from the slits.

Q3 Try putting different colored filters in front of the double slits. What are the differences between the pattern formed in blue light and the pattern formed in red or yellow light?

Measurement of wavelength

Remove the Scotch tape screen from the inside end of the narrow tube. Instead put a magnifying eyepiece and scale unit in the other end of the narrow tube and look through it (see Fig. 4). What you see is a magnified view of the interference pattern in the plane of the scale. Try changing the distance between the eyepiece and the double slits.

In Experiment 31 you used the formula

$$\lambda = \frac{x}{\ell} d$$

to calculate wavelength.

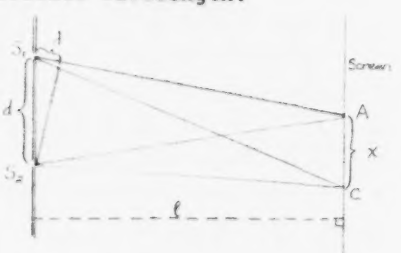


Fig. 3

Q4 Use the formula here to find the wavelength of the light transmitted by the different colored filters. Measure x, the distance between successive dark fringes, with the measuring magnifier.

Remember that the smallest divisions on the scale are 0.1 mm. ℓ is the distance from the slits to the plane of the pattern you measure. You can also use the magnifier to measure d, the distance between the two slits. (Place the film right up against the scale, and hold the film up to the light.)

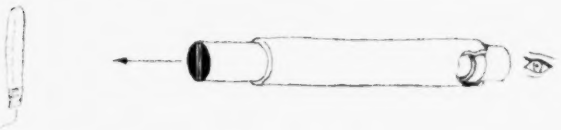


Fig. 4

Q5 The speed of light in air is approximately 3×10^8 meters/second. Use your measured values of wavelength to calculate the approximate frequencies for light of each of the colors you used.

Discussion

Q6 Why couldn't we use the method of "standing waves" (Experiment 31) to measure the wavelength of light?

Q7 Is there a contradiction between the statement, "light consists of waves" and the statement, "light travels in straight lines?"

Q8 Can you think of any everyday phenomenon in which the wave nature of light is important?

Suggestions for some more experiments

1. Examine light diffracted by a circular hole instead of a narrow slit. You will need a small point source of light instead of a long narrow one. Look also for the interference effect with light that passes through two small circular sources—pin holes in a card—instead of two narrow slits. Thomas Young used circular openings rather than slits in the original experiment (1802).

2. Look for the diffraction of light by an obstacle. Use straight wires, of various diameters parallel to a narrow light source, or circular objects like

tiny spheres, the head of a pin, etc. and a point source of light. You can use either method of observation—the Scotch tape screen, or the magnifier. You may have to hold the magnifier fairly close to the diffracting obstacle.

You will find instructions on how to photograph some of these effects in the activities for Chapter 13 of this Handbook.

3. Take two clean microscope slides and press them together. Look at the light they reflect from a source of light, like a mercury lamp or sodium flame, that emits light at only a few definite wavelengths. What you see is the result of interference between light reflected at the two inside surfaces that are almost, but not quite, touching. This method is used to measure very small distances in terms of the known wavelength of light of a particular color.

It can also be used to determine the flatness of surfaces. If the two inside surfaces are planes, the interference fringes are parallel lines. Bumps or depressions as small as a fraction of a wavelength of light can be detected as wiggles in the fringes.

Miscellaneous Light Activities*

ACTIVITY Scattered light

Add about a quarter-teaspoon of milk to a drinking glass full of water. Set a flashlight about two feet away so it shines on the glass. When you look through the milky water towards the light it has a pale orange color. As you move around the glass, the milky water appears more bluish as you view it from the side.

ACTIVITY Artificial rainbow

The rainbow effect seen from an airplane can be produced by using a glass of water as a large cylindrical raindrop. Place the glass on a piece of white paper in the early morning or late afternoon sunlight. To make the rainbow more visible, place two books upright, leaving a space a little wider than the glass between them, so the sun shines on the glass, but shading the white paper (Fig. 1). The rainbow will be seen on the backs of the books. You will find that light making the left side of the rainbow entered the glass on the right, and vice versa.

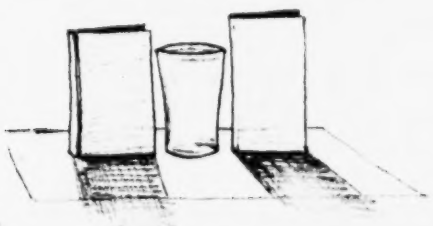
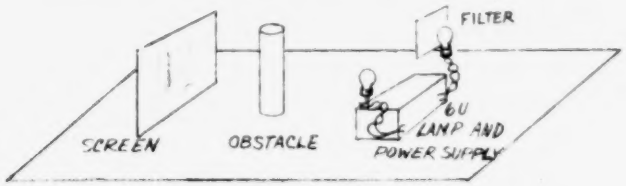


Fig. 1

*(Both activities are described in Science for the Airplane Passenger, by Elizabeth A Wood, to be published in March, 1968 by Houghton-Mifflin Co.)

ACTIVITY Color vision by contrast (Land Effect)

Hook up two small lamps as shown in the diagram. Place an obstacle in front of the screen so that adjacent shadows are formed on the screen. Do the shadows have any tinge of color? Now cover one bulb with a red filter, and notice that the other shadow appears green by contrast.



Try this with different colored filters and also vary the light intensity by moving the lamps to various distances.

Properties of the Human Eye

ACTIVITY Blind spot

Where the optic nerve leaves the eyeball, there are no photosensitive cells. To confirm this, close the left eye and bring the cross on the page directly toward the right eye. At a distance of

+ ●

approximately 10 inches, the spot will disappear, since it has been brought to focus on the blind spot. What do you see

B.C. By John Hart

I WONDER IF WE ALL SEE COLORS THE SAME.
..LIKE, ..GREEN TO YOU MIGHT LOOK RED TO ME, EVEN THOUGH I CALL IT GREEN TOO!
RIDICULOUS.
OK, ..WHAT COLOR IS THAT ROCK TO YOU?
GREY!
WRONG!

By permission of John Hart and Field Enterprises Inc.

where the spot should be? Try different backgrounds (white spots on black paper, colored paper) and study what you see where the spot should be.

ACTIVITY Inversion of image

Make a 1/16" diameter hole in a file card. Draw an arrow about 1/4" long (↑) on a clear microscope slide. Hold the card about 3" away from your eye, and look through the hole at a light bulb about 4' away. Now move the slide across between your eye and the card so that the point of the arrow passes in front of the hole in the card. A shadow of the arrow is formed on your retina. Why does the arrow appear inverted? (The arrow is too close to the eye to form a real image.) Note: A pin can be used instead of the arrow on the slide if you are very careful!

ACTIVITY Near point and accomodation

Bring this page toward the eye until you can no longer focus on the letters. The "near point" of the eye is the position inside which an image cannot be clearly focused. Look through a pinhole at the page, and you will see a reasonably clear image even very close to the eye. Note how large the letters look. Try reading a newspaper in bright sunlight to see if you can bring the page into focus closer to your eye than you can when the page is in shadow. (See activity on the iris for possible explanations.)

ACTIVITY The iris

The size of opening in the iris of the eye (pupil) depends on the amount of light present. Measure the diameter of your pupil by viewing a millimeter scale in a mirror held about 4 cm away. Measure the pupil diameter in high and low light. While measuring the diameter of one pupil shine a light in the other eye. Are both pupils affected by light that strikes just one?

ACTIVITY Dark-adaption-vision by rods and cones

The fovea of the eye is the central area of most acute vision. Cone-shaped light receptors are abundant in the fovea. These cones are sensitive to light of different wavelengths (various colors). Rod-shaped receptors are not common in the fovea, and are not color sensitive, but are more sensitive to dim light than are the cones. To illustrate this, allow your eyes to become accustomed to total darkness. (This dark-adaption takes about 30 minutes to complete, but the experiment can be done successfully after about 5 minutes.) With a Variac, slowly increase the current in an unfrosted lamp bulb until it just begins to glow and you can see it when you look slightly to one side. The filament will appear greyish-white. Slowly increase the current, looking alternately at and to one side of the filament. (The paperback Experiments in Seeing, by Harry Asher, Fawcett Publications, (1961), is a good source for further activities and information. Also see Light and Vision, Life Science Library, 1966.)

ACTIVITY Make an ice lens

Dr. Clawbonny, in Jules Verne's The Adventures of Captain Hatteras, was able to light a fire in -48° C weather (thereby saving stranded travelers) by shaping a piece of ice into a lens and focusing it on some tinder. If ice is clear, the sun's rays pass through with little scattering. You can make an ice lens by freezing water in a round-bottomed bowl. Use boiled distilled water, if possible, to minimize problems due to gas bubbles in the ice. Measure the focal length of the lens and relate this length to the radius of the bowl. (Adapted from Physics for Entertainment, Y. Perelman, Foreign Languages Publishing House, Moscow, 1936.)

ACTIVITY Polarized Light Activities

The shock wave that is now spreading throughout the field of optics in general, and polarized light in particular, is the result not so much of an explosion as of an implosion. The laser, our most intense laboratory source of polarized light, was invented by researchers in electronics and microwaves. Botanists have discovered that the direction of growth of certain plants can be determined by controlling the polarization form of the illumination, and zoologists have found that bees, ants, and various other creatures routinely use the polarization of sky light as a navigational "compass." High-energy physicists have found that the most modern particle accelerator, the synchrotron, is a superb source of polarized x rays. Astronomers find that the polarization of radio waves from planets and from stars offers important clues as to the dynamics of those bodies. Chemists and mechanical engineers are finding new uses for polarized light as an analytical tool. Theoreticians have discovered short-cut methods of dealing with polarized light algebraically. From all sides the inrush of new ideas is imparting new vigor to this classical subject.

Detecting polarized light

Polarized light can be detected directly by the unaided eye, provided you know what to look for. To develop this ability, begin by staring through a sheet of polaroid at the sky for about ten seconds. Then quickly turn the polarizer 90° and look for a pale yellow brush-shaped pattern similar to the sketch in Fig. 1.

The color will fade in a few seconds, but another pattern will appear when the polaroid is again rotated 90°. A light blue filter behind the polaroid may help.

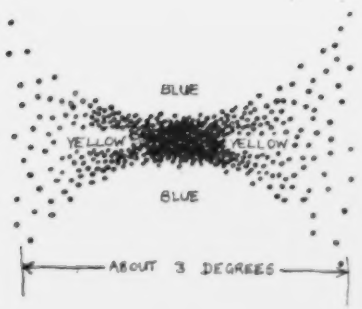


Fig. 1

It is not easily seen using an ordinary incandescent bulb.

There are several interesting aspects:

(a) How is the axis of the brush related to the direction of polarization of light transmitted by the polaroid? (To determine the polarization direction of the filter, look at light reflected from a horizontal non-metallic surface, such as the floor. Most of the reflected light has its axis of polarization parallel to the floor. Turn the polaroid until the reflected light is brightest. It is useful to make a scratch or put tape on one edge of the polaroid parallel to the floor to show the direction of polarization.) Does the axis of the yellow pattern always make the same angle with the axis of polarization?

(b) Some people can see the brush without using the polaroid. Try it, looking at a clear blue sky. In what direction, relative to the sky, is the pattern clearest?

(c) Some people see the brush clearest when viewed with circularly polarized light. (To make a circular polarizer, place a piece of polaroid in contact with a piece of cellophane with its axis of polarization at a 45° angle to the fine stretch lines of the cellophane.) (Adapted from Polarized Light, W. A. Shurcliff and S. S. Ballard, Van Nostrand Momentum Book #7, 1964.)

The set-up: Photographer Chris Smith takes five pictures simultaneously with a battery of linked cameras mounted on a wooden stand as Roger Fidler hits a full drive.

On this camera the shutter aperture was moving from the bottom of the picture to the top and as a result the image of the club-head was exposed on the film fractionally before the hands. This gives a distortion which makes it appear that the club shaft is bending backwards. It is from pictures of this type that one of golf's great fallacies arises—that the hands must lead the club-head into the ball. It is, in short, the much prized 'late hit' which must henceforth be relegated to the realms of mythology.

ACTIVITY The Camera DOES Lie!

An article by Peter Dobereiner in the Observer, (London), December 17, 1967 included the five photographs shown on these two pages to illustrate an important point about camera distortions.

A simple experiment which you can perform at home with your TV set may help you to understand more about the problem discussed here. Hold one finger pointing upwards at arm's length in front of you, and move it fairly rapidly from left to right between you and a television screen You won't see a blurred image as you do when you wave your finger across while viewing a light colored wall. Instead you will see a series of discrete images of your finger, because of the way the electron beam scans the screen and the persistence of vision of your eye (see Fig. 1). Furthermore, the image seems to bend backward because your finger

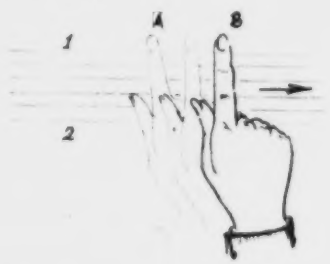


Fig. 1

has moved from A to B while the scanning beam has moved from 1 to 2. A more dramatic effect results when you point your finger downward and move it from

Here is exactly the same moment in time taken on a camera with the shutter aperture moving from top to bottom. In this case the hands were snapped before the club-head, which had time to advance several inches and almost make contact with the ball. Notice that the hand position in all the pictures is virtually the same. In this type of camera the distortion frequently suggests that the shaft is bending forward and from this photographic trick many teachers have deduced that extra zip is imparted to the ball by the whipping action of the shaft.

Probably the most accurate representation of the impact position, this picture was taken on a camera with the aperture moving from left to right. From this angle the shaft appears to be virtually straight (although in fact it is bowing slightly towards the camera). The club-head at this point is moving at something like 170 feet per sec. and the shutter, travelling in the same direction, has 'frozen' it in pretty much its real position. All these first three cameras were of the focal plane type, of modern design and popular today for sports photography.

This is the only picture taken with a camera having a compur shutter, which takes in the whole scene at once. At this speed (1/500 sec.) there is blurring in direct proportion to the speed of the different parts of the subject. Pictures of this kind give a cinematic effect, showing the relative movement of hands and club-head during the business part of the swing. The deduction which can be drawn is that talk of 'a fast hand action in the impact zone' is so much hog-wash. Power comes from the sweep of the club-head past the line of the arm.

left to right: your finger seems to point <u>forward</u>.

A camera which has a focal plane shutter may cause a similar distortion of an image. A focal plane shutter is much like a window blind with a slit cut in it (Fig. 2).

Fig. 2

When the shutter release is pressed, the slit moves across the film, so an area the size of the slit is exposed at each instant. Distortion is worst when an object is moving at high speed perpendicular to the direction of motion of the slit.

In the case of the golfer, if the slit is moving from top to bottom, during the time the slit takes to cover the area from hands to the ground the club head will have moved several inches further

forward, giving the impression that the club curves forward.

The other type of camera shutter, the compur, works more like a blink of an eye (Fig. 3).

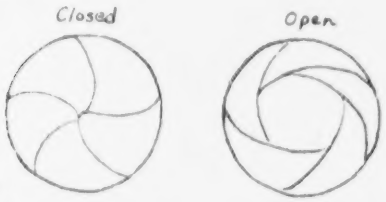


Fig. 3

The film gets a quick flash of the whole subject and any fast movement is represented as a blur on the picture.

If you now look at the five photographs you will see the different possible distortions caused by different kinds of shutters moving in different directions. All pictures were taken at 1/500 second at precisely the same moment.

Why is the photograph on page 126 of the Unit 1 Reader not subject to the same distortions? (Adapted from "Why the Camera is a Blinking Liar," The Observer, December 17, 1967. Photos by Chris Smith, courtesy The Observer.)

ACTIVITY Matching index of refraction

Transparent objects are visible because their index of refraction is different from their surroundings. Glass, for example, is visible when submerged in water because the index of refraction of glass is greater than that of water. Some light is reflected at the interface. If the indexes of refraction of a liquid and a solid are equal, the boundary disappears. Crown glass has an index of refraction of slightly more than 1.5. Place a piece of glass in a small beaker and add a few ml of benzene (n = 1.51). Then add, drop by drop, carbon disulfide (n = 1.61) until the boundary becomes indistinct. What happens when you add further carbon disulfide? When the boundary was most indistinct, did you notice any colors near the glass? Did they change as liquid was added? CAUTION: Carbon disulfide and benzene are both highly flammable.

ACTIVITY Handkerchief diffraction grating

Stretch a good quality linen or cotton handkerchief and look through it at a distant light source, such as a streetlight about one block away. You will see an interesting diffraction pattern. (A cloth umbrella will also work.)

ACTIVITY Seeing and photographing diffraction patterns

Diffraction patterns like the one below and on page 33 of your text can be produced in your lab or at home. The photo in Fig. 1 was produced with the setup diagrammed in Fig. 2.

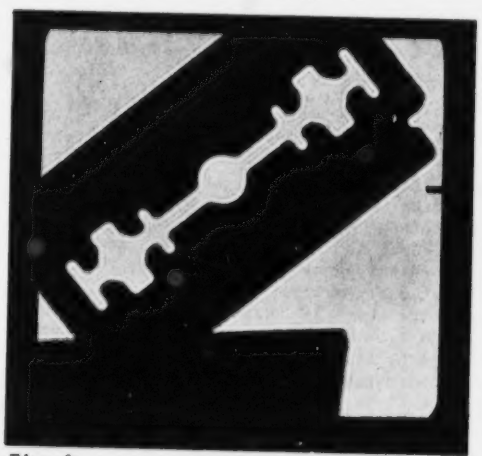
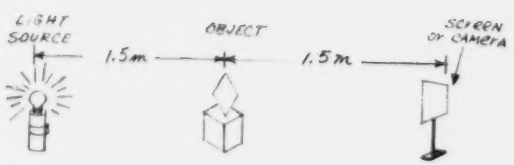
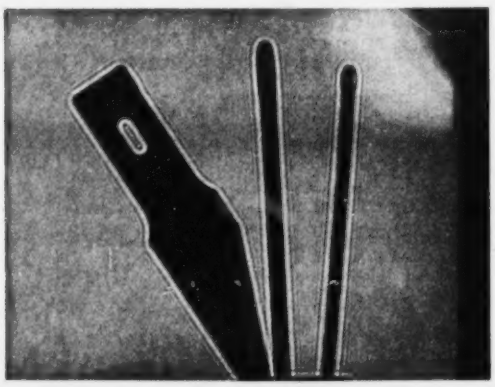


Fig. 1



As a light source use a 1 1/2 volt flashlight bulb and AA cell. Turn it so the end of the filament acts as a point source. A red (or blue) filter makes the fringes sharper. You can see the fringes by examining the shadow on the screen with the 10x magnifier. Razor blades, needles, or wire screen make good objects.



To photograph the patterns you must have a darkroom or a large light-tight box. Figure 1 was taken using a Polaroid 4 × 5 back for a Graphic press camera. The lens was removed, and single sheet 3000-speed Polaroid film was exposed for 10 seconds; a piece of cardboard in front of the camera was used as a shutter.

The procedure is more involved when you use a model 002 Polaroid camera, since the lens cannot be removed. The following procedure has been successful, but we advise a dry run using an empty film pack first.

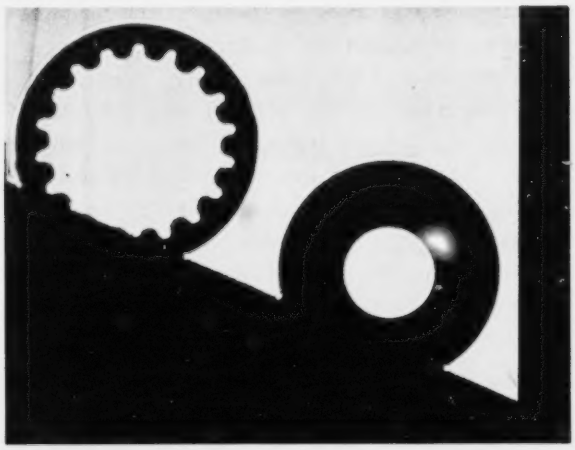
With lights on:

1. Set up the parts: check that the shadow is projected on the screen. Mark the location on the screen.
2. Remove the screen and clamp a new film holder in its place.

ALL LIGHTS OUT (room and source).

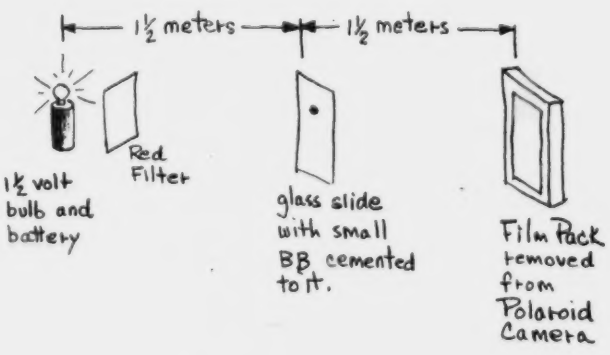
3. Pull tab to expose first sheet of film.
4. Place sheet of cardboard in front of pack to act as "shutter."
5. Have partner turn on source.
6. Remove cardboard shutter for 2 or 3 seconds. Replace cardboard.
7. Turn off source.
8. With room lights still out, replace pack in camera and close back. Pull tab to develop film as in normal procedure.

NOTE: For 2nd, 3rd, etc. shots on the same pack, you must remove the pack from the camera and clamp it in position, ALL IN TOTAL DARKNESS, because the pack has no protective cover after it is opened. Exposures given are only approximate; you will have to find out which works best for your setup.



ACTIVITY Poissons spot

A bright spot can be observed in a photograph of the center of some shadows. To see this, set up a light source, obstacle and screen as shown. Satisfactory results require complete darkness. Try a two-second exposure (with Polaroid 3000 film) as your first exposure.


1½ meters
1½ meters
Red Filter
1½ volt bulb and battery
glass slide with small BB cemented to it.
Film Pack removed from Polaroid Camera

ACTIVITY Miscellaneous Photography Activities

As the number of photography activities is limitless, we shall not try to describe many in detail. Rather this is a collection of suggestions to give you a "jumping-off" point for classroom displays, demonstrations and creative work.

(a) History of photography

Life magazine, December 23, 1966 had an excellent special issue on phctography. How the world's first trichromatic color photograph was made by James Clerk Maxwell in 1861 is described in Scientific American, November 1961. Many early processes are described in the Science Study Series paperback, Latent Image, by Beaumont Newhall. Much of the early history of photography in the United States is discussed in Mathew Brady, by James D. Horan, Crown Publishers. The Unit 4 Project Physics Teacher Guide also contains a photographic instrumentation bibliography.

(b) Schlieren photography

For a description and instructions for equipment, see Scientific American, February 1964.

(c) Land two-color demonstrations

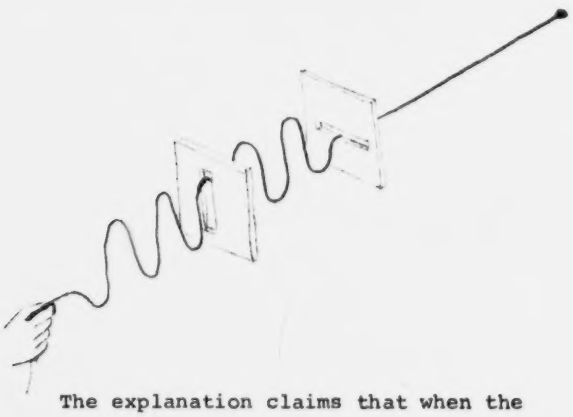
A difficult but interesting activity is to demonstrate that a full-color picture can be created by simultaneously projecting two black-and-white transparencies taken through a red and a green filter. For more information see Scientific American, May 1959; September 1959; and January 1960, and The Physics Teacher, 1968.

(d) Infrared photography

Try to make some photos like the ones shown on page 122 of your text. Kodak infrared film is no more expensive than normal black-and-white, and can be developed with normal developers. If you have a 4 x 5 camera with a Polaroid back, you can use 4 x 5 Polaroid infrared film sheets. You may find the Kodak Data Book M-3, "Infrared and Ultraviolet Photography," very helpful.

Polarization problem

At some time you may have had polarization of light explained to you in terms of a rope which is tied to a fixed object at one end, and being shaken at the other end. In between, the rope passes through two slotted pieces of cardboard.



The explanation claims that when the slots are parallel the wave passes through, but when the slots are perpendicular the waves are stopped.

Place two Polaroid filters as shown in Fig. 1 and turn one so that it blacks out the light completely. Then place a third filter between the first two, and rotate it about the axis of all three. What happens? Does the "picket fence" analogy still hold?

A similar experiment can be done with microwaves, using parallel strips of tinfoil on cardboard instead of Polaroid filters. (See Polarized Light, Shurcliff and Ballard, Momentum paperback #7.)

Scattering problem

You have seen the light scattered by dust and water droplets in the atmosphere after sunlight streams through openings in a clouded sky, such as on page 4 of the Unit 4 text. The physics of the scattering, the dependence on the size of the scattering particle and the wavelength of the light are challenging but not simple problems.

One problem you can work on is this: Estimate the angle between the beams at the left and the right of the picture on page 4, Unit 4 text. Make some estimate in miles of the distance between the points where these rays strike the ground. Use the triangle to make a roughly graphical estimate of the height of the point from which the rays diverge. Can it be the sun? What do you think is happening here? (Adapted from "Little Stinkers," in the January, 1964 issue of The Physics Teacher.)

Faster than the speed of light?

In the photograph below you can see that the ball is squashed and distorted as the bat hits it. But also note that the shadow of the ball on the ground has not made contact with the shadow of the bat.

Consider the following proposal: "The discrepancy results from the delay in time that it takes light to reach the ground from the ball." You can estimate how fast the bat would have to be moving by estimating a) the bat-ball distance, b) the bat shadow-ball shadow distance, c) the ball-ground distance, and d) the speed of light (about 10^9 ft/sec.). In the time it takes light to travel from bat level to ground (about 24") and there form a shadow, the bat has traveled the short distance (about 4") between shadows of the bat and ball.

Activities

NOTE: The photograph was not retouched in any manner. It is an actual photograph. If you don't accept the previous proposal, what other possible explanations can you think of which explain the picture? Hint: Another activity in this chapter of the Student Handbook is quite helpful. (Adapted from The Physics Teacher, November, 1963, p. 241.)

EXPERIMENT 33 Electric Forces I

If you walk across a carpet on a dry day and then stretch out your hand to a metal door knob, a spark may jump across between your fingers and the knob. You can get a fatter and longer spark if you shuffle instead of stepping. Your hair may crackle as you comb it. You have probably noticed other examples of the electrical effect of rubbing two objects together. Does your hair ever stand on end when you pull off your clothes? (This works particularly well if the clothes are made of nylon, or one of the other synthetic fibers.)

Small pieces of paper are attracted to a plastic comb or ruler that has been rubbed on a piece of cloth. Try it. The attractive force is often large enough to lift the scrap of paper off the table, showing that it is stronger than the gravitational force between the paper and the entire earth! The force between the rubbed plastic and the paper is an electrical force, one of the four basic forces of nature. [The other forces are the gravitational, the strong-nuclear, and the weak-nuclear.] In this experiment you will make some observations of the nature of the electrical force, and if you do the next one (Experiment 34, Electric Forces II) you will be able to make quantitative measurements of the force.

Forces between electrified objects

Unroll about an 8-inch length of Scotch tape and stick it to the table. Press it down well with your finger. Tear it off the roll, but make sure you leave an inch or so loose as a handle. Now remove the tape from the table by pulling on this loose end; be careful to prevent the tape from curling up around your fingers.

Q1 To test whether your tape became charged (electrified) when you stripped it from the table, see whether it will pick up a scrap of paper. Of course you must be sure that the paper isn't simply sticking to the stickum on the tape. Will the paper stick to the non-sticky side? Or, an even better test, will the paper jump up from the table to the tape? Is the tape charged?

So far we have only considered the effect of a charged object (the rubbed comb, the tape) on an uncharged one (the scrap of paper). What effect does a charged object have on another charged object? Here is one way to test it.

Charge a piece of tape by sticking it to the table and peeling it off as you did before, and this time suspend it from a horizontal rod, or over the edge of the table. (Don't let the lower end curl around the table legs!)

Now charge a second strip of tape in the same way, hold it at the top and bring it close to the first one. It's a good idea to have the two non-sticky sides facing.

Fig. 1

Q2 What happened? Did the two tapes affect each other? Was there a force on either tape, or on both? What kind of a force was it—attractive or repulsive?

Hang the second tape up a few inches away from the first one. Proceed as before to electrify a third piece of tape and observe the reaction between it and your first two tapes. Record all your observations. Leave the first tape hanging from its support—you will need it again.

Stick a new piece of tape down on the table and then stick another tape over it. Press down well. Peel the two stuck-together tapes from the table and then very carefully pull the two tapes apart.

Q3 Did you notice any interaction between them (other than those due to the stickum) as you separated the tapes?

Q4 Hold one of these just-separated tapes in each hand and bring them slowly towards each other (non-sticky sides facing). What do you observe?

Q5 Now bring first one, then the other of this pair near to your original test strip. What happens?

Hang up these last two strips from your support, but far enough apart so that they don't get tangled up with each other. Call one A, the other B.

If you have rods of plastic, glass or rubber available, or a plastic comb, ruler, etc., charge them by rubbing on cloth or fur and bring them in turn close to A and then B. If you don't have any such objects available, try the same thing with pieces of Scotch tape electrified by being stuck to the table and then peeled off. Record your observations.

Q6 What pattern of behavior do you notice? How do A and B differ in behavior? When you have observed the interaction between a charged object and A, can you predict how it will interact with B?

By now you should have had ample evidence that the forces between electrified objects can be repulsive as well as attractive.

Q7 Classify all the electrified objects you tested by their behavior: make a table showing in one column the objects that were attracted by A and in the other those attracted by B. Where do you place A and B themselves in this table? What is the reaction when a charged object in the "attracted by A" group is brought near to B?

From the results of a limited number of experiments you cannot prove that all electrified objects will fall into one, and only one, of your columns. But in fact no one has ever produced an electrified object that either attracts, or repels, <u>both A and B</u> (where A and B are themselves electrified objects that attract each other). There are only two classes of electrified objects: all members of the same class repel each other, and attract all members of the other class.

The two classes are called + and - and, on the established convention (which dates from Benjamin Franklin's work), the charge that is added to a comb when you comb your hair is -. The electron (see Sec. 14.5) is negatively charged.

In normal, uncharged matter there are as many positively charged particles (protons) as electrons. When you comb your hair some electrons are transferred from your hair to the comb, giving the comb a negative charge. There are now more protons than electrons left in your hair so it has a positive charge.

Fig. 2

A puzzle

Our system of two classes of electrified objects was based on observations on the way charged objects interact. But how can we account for the fact that a charged object (rubbed-comb) will attract an uncharged one (scrap of paper)? You should check for yourself that the force between a charged body (either + or -) and an uncharged body is always attractive, never repulsive.

Q8 Can you explain how this force arises and why it is always an attraction? The clue here is the fact that electrons can move about slightly even in materials that we call non-conductors, like plastic and paper.

For Discussion

Which of the four basic forces—gravitational, electrical, weak-nuclear, strong-nuclear—do you think it is that makes things stick to the sticky side of the Scotch tape? The same force holds atoms together in molecules, and molecules together in crystals, and is responsible for the frictional force between sliding bodies.

In some ways the forces between electrified objects seem similar to the forces between magnets: they can be attractive or repulsive; a charged object attracts an uncharged one and a magnet attracts a non-magnetized piece of steel. List as many ways as you can in which the two effects differ.

EXPERIMENT 34 Electric Forces II — Coulomb's Law

You have seen that electrically charged objects exert forces on each other, but so far your observations have been qualitative; you have looked but not measured. In this experiment you will find out how the electrical force between two charged bodies depends upon the amounts of charge and on their separation. In addition, you will gain experience with some of the difficulties of using sensitive equipment.

The electric forces between charges that we can conveniently produce in a laboratory are small. To measure them at all requires a sensitive balance.

Constructing the balance

(If your balance is already assembled you need not read this section—go straight to "Using the balance.")

The balance is shown in Fig. 1.

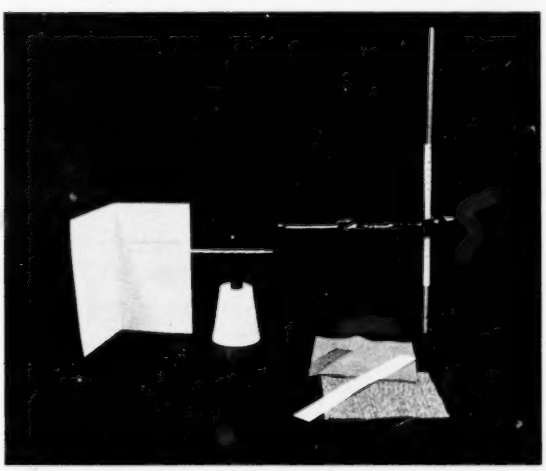


Fig. 1

Coat a small light ball with a conducting paint and fix it to the end of a plastic sliver or toothpick by stabbing the pointed end into the ball. (If the spheres are uncoated or the plastic slivers are not precut, your instructor will tell you how to prepare them.) Hold the other end of the sliver or toothpick in a clamp on a ringstand. Push another similar ball-and-sliver into one end of a soda straw (not too far!). Since it is very important that the plastic be clean and dry (to reduce leakage of charge along the surface), handle the plastic slivers as little as possible, and then only with clean, dry fingers.

Next, form the support for the balance. In a plastic pill vial, or the small tube that the coater for Polaroid film comes in, cut two notches, about 3/8 inch wide and 1/2 inch deep, on opposite sides of the tube (Fig. 2). At right angles to this axis, make two shallow, smooth notches by pressing a hot nail against the plastic.

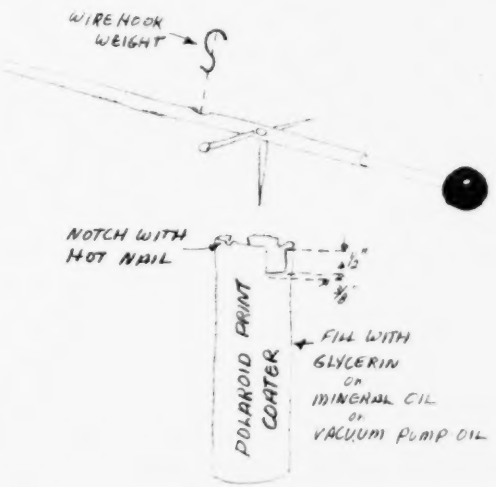


Fig. 2

Secure the tube to a book or block (or use a plastic coffee cup), so that the bottom is at least two inches above the table top. Fill the tube with glycerine, mineral oil, or vacuum pump oil.

Next, locate the balance point of the straw, ball and sliver unit. Push a pin through the straw at this point to form an axle. Push a second pin through the straw directly in front of the axle and perpendicular to it. (As the straw sways

back and forth, this pin moves through the fluid in the support tube. The fluid damps the swings of the balance.) Cut a shallow (!) notch in the top of the straw about 2 cm from the axle on the side away from the sphere—see Fig. 2. Place the balance on the support, the pin hanging down inside the vial. Now adjust the balance, by sliding the plastic sliver slightly in or out of the straw, until the unweighted straw rests horizontally. If necessary, stick small bits of tape to the straw to effect a proper balance. Make sure that the balance can swing freely while you are making this adjustment.

Using the balance

Charge both balls by touching them with a rubber plastic strip. Then bring the ringstand ball down towards the balance ball from above it.

Q1 What evidence have you that there is a force between the two balls?

Q2 Can you tell that it is a force due to the charges?

Q3 Can you compare the electrical force between the two balls with the gravitational force between them?

Finally, cut five or six small equal lengths of thin wire (#30 copper). They should be about 2 cm long, and they must all be as close to the same length as you can make them. Bend them into small hooks (Fig. 2) that can be hung over the notch in the straw or hung from each other. These are your "weights."

Your balance is now ready, but one more problem needs to be solved. During the experiment you will adjust the position of the ringstand sphere so that the force between the charged spheres is balanced by the "weights." The straw will then be horizontal. How can you tell, quickly, that the straw is balanced horizontally each time, and how can you measure the distance between the centers of the two balls? You cannot put a ruler nearer to the charged balls than about 5 cm, or its presence will affect your results.

With your balance in its horizontal position, you can record this "balanced position" with a mark on a folded card placed near the end of the straw that will be away from the charges. (See Fig. 1.) Try to devise a method for measuring the distance between the centers of the balls. Ask your instructor if you cannot think of one.

You are now ready to begin the experiment.

The experiment

Hang one hook over the notch in the straw. From now on, move carefully to avoid disturbing the balance or creating air currents, but work as quickly as possible. For example, it is not necessary to wait for the straw to stop moving before you record its position. When it is swinging slightly, but equally, to either side of the balanced position, you can consider it balanced.

Charge both balls, touch them together briefly, and move the ringstand ball upward until the straw is returned to the balanced position. The weight of one hook now balances the electric force between the charged spheres when at this separation. Record (or have your partner record) the position of the upper ball.

Without recharging the balls, add a second hook and readjust the system until balance is again restored. Record this new position. Repeat until you have used all the hooks—but don't reduce the air space between the balls to less than 0.5 cm. Then quickly retrace your steps by removing one (or more) hooks at a time and raising the ringstand ball each time to restore balance.

Q4 The separations recorded here may or may not agree with your previous measurements with this same number of hooks. If they do not, can you suggest a reason why?

Q5 Why must you not recharge the balls between one reading and the next?

Conclusion

Make a graph of your measurements of force F against separation between centers, d. Clearly F and d are inversely related, that is, F increases as d decreases. But we can go further and find out what the relationship is between F and d; it might be $F \propto 1/d$, $F \propto 1/d^2$, or $F \propto 1/d^3$, etc.

Q6 How would you test which of these best represents your results?

Q7 What is the relationship between F and d?

Further Study

As a further project you can find out how the force F varies with the charges on the spheres, when d is kept constant.

Charge both balls and then touch them together briefly. Since they are nearly identical, it is assumed that, when touched, they will share the total charge almost equally.

Hang four hooks on the balance and move the ringstand ball until the straw is in the balanced position. Note this position.

Touch the upper ball with your finger to discharge the ball. Now if the two balls are again brought into contact, the charge left on the balance ball will be shared equally between the two balls.

Q8 What is the charge on each ball now (as a fraction of the original charge)?

Return the ringstand ball to its previous position and find out how many hooks you must remove to restore the balance.

Q9 Can you state this result as a mathematical relationship between quantity of charge and magnitude of force?

Questions

1. You may want to consider why two precautions were described in the experiment notes:
   (a) Why can a ruler too close to the charge affect results?
   (b) Why was it suggested that you get the spheres no closer than about 0.5cm?
2. How might one modify this experiment to see if Newton's third law applies to these electric forces?

EXPERIMENT 35 Forces on Currents

Introduction

If you did Experiment 34, you used a simple but sensitive balance to investigate how the electric force between two charged bodies depends on the distance between them and on the amount of charge. In this and the next experiment you will examine a related effect: the force between moving charges, that is, between currents. Before starting the experiment you should have read the description of Oersted's and Ampère's work in the text (Secs 14.11, 14.12).

The apparatus for these experiments is similar in principle to the balance you used to measure electric forces. The current balance measures the force on a horizontal rod suspended so that it is free to move in a horizontal direction at right angles to its length. You can study the forces exerted by a magnetic field on a current by bringing a magnet up to this rod while there is a current in it. A force on the current-carrying rod will cause it to swing away from its original position.

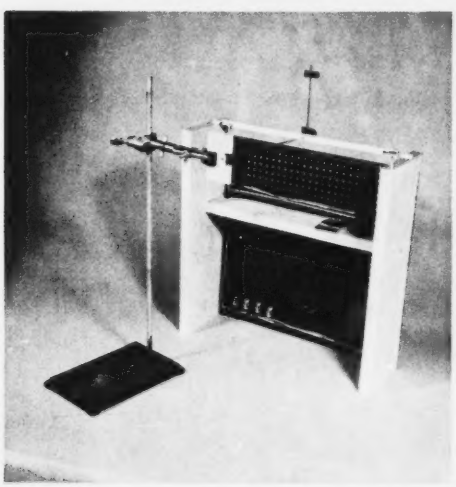


Fig. 1

You can also pass a current through a fixed wire parallel to the pivoted rod. Any force exerted on the rod by the current in the fixed wire will again cause the pivoted rod to move. You can measure these forces simply by measuring the counter force needed to return the rod to its original position.

The current balance

The instrument is more complicated than most you have worked with so far; therefore it is worthwhile spending a little time getting to know how the instrument operates before you start taking readings.

1. There are three or four light metal rods bent into ⌊‾⌋ or ⌊‾⌋⌊ shapes. These are the movable "loops." Set up the balance with the longest loop clipped to the pivoted horizontal bar. Adjust the loop so that the straight part hangs level with the bundle of wires (the fixed coil) on the pegboard frame. Set the balance on the frame so that the loop and coil are parallel as you look down at them. They should be about at least five centimeters apart. Make sure the loop swings freely.

2. Use the "counterweight" cylinder behind the loop to balance the system so that the long pointer arm is approximately horizontal. Mount the ⊏ shaped plate (zero-mark indicator) in a clamp and position the plate so that the zero line is opposite the horizontal pointer. (If

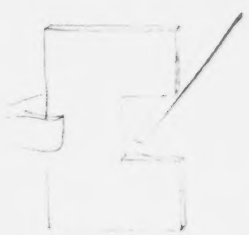


Fig. 2 Set the zero mark level with the pointer when there is current in the balance loop, no current in the fixed coil.

you are using the equipment for the first time, you will have to draw the index line yourself.)

3. Now set the balance for maximum sensitivity. To do this, move the spring clip (the sensitivity clip) up the vertical rod (Fig. 3) until the loop swings

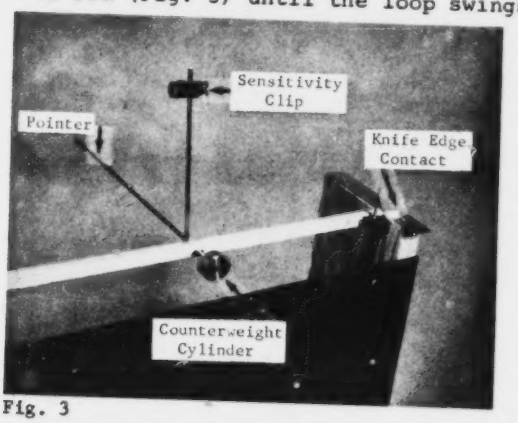


Fig. 3

back and forth slowly. These oscillations may take as much as four or five seconds per swing. If the clip is raised too far, the balance may become unstable and flop to either side without "righting" itself.

4. Connect a 6 to 8V dc power supply that can supply up to 5 amps through an ammeter, then through a rheostat to one end of the loop. (Make contact to the flat horizontal plates on which the pivots rest.) Connect the other plate to the other terminal of the power supply.

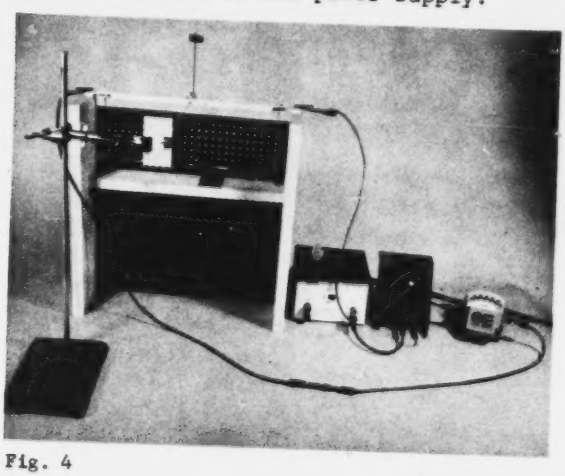


Fig. 4

5. Set the rheostat to maximum resistance, and turn on the power supply. If the ammeter deflects the wrong way, interchange the leads to it. Slowly increase the current up to about 4 amps.

6. Now bring a small magnet close to the pivoted conductor.

Q1 Is there a force on the current-carrying rod?

Q2 How must the magnet be placed to have the biggest effect on the rod? Try the magnet in various positions. What determines in which direction the rod swings?

Q3 Does the rod respond to all forces—or only forces in a particular direction?

Turn off the current.

You will make quantitative measurements of the forces between magnet and current in Experiment 36. The rest of this experiment is concerned with the interaction between two currents.

The interaction between two electric currents

7. Connect a similar circuit (power supply, ammeter, rheostat) to the fixed coil on the vertical pegboard—the bundle of ten brown wires, not the single colored one. The two circuits are independent and there must be an ammeter and rheostat in each one. Your setup should now look like the one shown in Fig. 5.

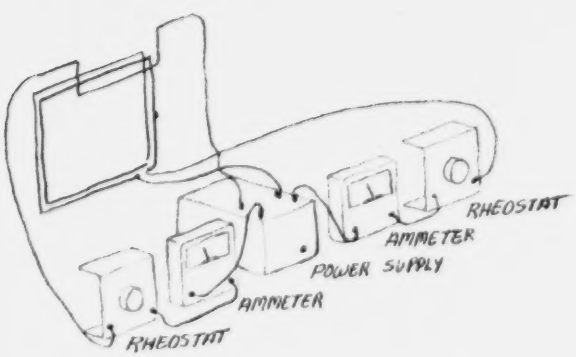


Fig. 5

8. Turn on the currents in both circuits and check to see which way the pointer swings. It should move UP. If it does not, see if you can make the pointer swing UP by changing something in your setup.

9. Prepare some "weights" from the thin wire given to you. You will need a set that contains wire lengths of 1 cm, 2 cm, 5 cm and 10 cm. You may want more than one of each, but you can make more as needed during the experiment. Bend them into small S-shaped hooks so that they can hang from the notch on the pointer or from each other.

These preliminary adjustments are common to all the investigations. But from here on there are separate instructions on three different experiments. Different members of the class will investigate how the force depends upon:

A) the current in the wires.
B) the distance between the wires.
C) the length of one of the wires.

From the data gathered in these different investigations, you will be able to give a precise description of the force between two currents. In addition, you may be able to measure the force constant involved, i.e., what the actual force is, in newtons, between two known currents. When you have finished your experiment (A, B, or C) go on to read the section "For class discussion."

A. A study of force and how it changes with current in the wires

Set the balance on the frame so that the loop and coil are parallel as you look down at them. They should be about 1.0 centimeter apart.

Set the current in the balance loop to about 3 amps. Do not change this current throughout the experiment. Set the zero-mark in line with the pointer, with this current in the balance loop and no current in the fixed coil.

Starting with a small current (about 1 amp) in the fixed coil, find how many centimeters of weight wire you must hang on the notch in the pointer arm to balance the system, that is, to return the pointer to its zero position.

Record the current in the fixed coil, I_f, and the length of wire added to the pointer arm. (The weight of wire is the balancing force, F.)

Change the current in the fixed coil, I_f, to a larger value, and check to make sure that the current in the balance loop, I_b, has not changed. Hang more weights as needed to restore the system to balance.

Continue as above, checking the current in the balance loop as you vary I_f, until you reach currents of about 5 amps in the fixed coil.

Results

Q4 What is the relationship between the current in the fixed coil and the force on the balance loop? One way to investigate this, of course, would be to plot force F against the current I_f.

Q5 Suppose you had held I_f constant and measured F as you varied the current in the balance loop I_b. What relationship do you think you would have found between F and I_b? Check your answer, if you have time.

Q6 If the force on the balance loop is $\vec{F}$, what is the force on the fixed coil?

Q7 How do you convert the force as measured in centimeters of wire hung on the pointer arm into the conventional units for force, newtons?

B. A study of force and how it varies with the distance between wires

Set the zero mark with a current I_b of about 4.5 amps in the balance loop and no current I_f in the fixed coil.

To measure the distances between the two wires, you have to look down. Put a scale on the wooden shelf below the loop. Because there is a gap between the wires and the scale, what you read on the scale changes as you move your head back and forth. This effect is called parallax, and it must be reduced if you are to get good measurements. If you look down into a mirror set on the shelf, you can tell when you are looking straight down because the wire and its image will line up. Try it.

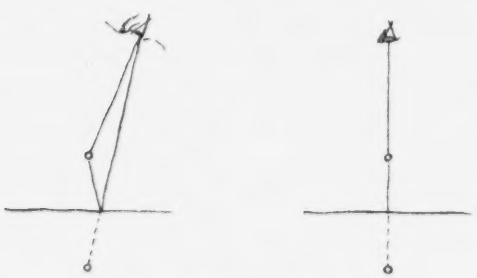


Fig. 1

Stick a length of centimeter tape along the side of the mirror so that you can sight down and read off the distance between the fixed wire and the balance loop.

But by distance we must mean something definite. In this case we measure the distance between the centers of the wires. You can locate these, using the anti-parallax mirror and scale, either by guesswork (not so good) or by measuring the diameters of the wires and dividing by two to find the radius. The distance between centers is, after all, just the distance between the near edges of the two wires (easily measured with your mirror unit) plus the radius of the balance loop (r_b), plus the radius of the fixed coil of wires (r_f).

Fig. 2

You are now ready to begin the experiment! Place the balance loop about 0.5 cm from the fixed coil. Set the zero mark with current (about 4.5 amps) in the balance loop, and no current in the fixed loop. Do not change this current once you have set the zero mark. Turn on the current in the fixed coil. It should also be about 4.5 amps.

Hang weights on the notch in the pointer arm until the pointer is again at the zero position. Once set, do not change either current again during the experiment.

Record the current in each wire, the distance between the wire centers, and the force (length of wire) that is needed to return the loop to its undeflected position.

Turn off the currents. Move the balance unit a little farther from the fixed coil. Loop and coil must be parallel to each other. Turn on the current in the balance loop and recheck the zero position. Since you have moved the balance, you may have changed the zero position slightly. Reset the zero mark.

Measure the new distance between wire centers with the pointer at the zero mark. Now turn on the current in the fixed coil, check that the currents have not changed, and add or remove weights until balance is restored. Record the values.

Repeat the process until you have values for the force for four or five different distances. You should try to get values at distances up to about 6.0 cm.

Results

Q8 Can you find the relationship between the force F and the distance d? Try to find some function of d ($1/d$, d^2,...) which gives a straight line when plotted against F.

Q9 If the force on the balance loop is F, what is the force on the fixed coil?

Q10 Can you see how to convert the force as measured in centimeters of wire hung on the pointer arm into the conventional units, newtons?

C. Force, and how it varies as the length of one of the wires is changed

Set the zero mark with a current, I_b, of about 4.0 amps in the balance loop and no current, I_f, in the fixed coil.

To measure the distances between the two wires, you have to look down. Put a scale on the wooden shelf below the loop. Because there is a gap between the wires and the scale, what you read on the scale changes as you move your head back and forth. This is parallax, and it must be reduced if you are to get good measurements. If you look down into a mirror set on the shelf, you can tell when you are looking straight down because the wire and its image will line up. Try it.

Stick a length of centimeter tape along the side of the mirror so that you can sight down and read off the distance between the fixed wire and the balance loop.

You are now ready to begin the experiment! Turn on the currents and hang weights on the notch in the pointer arm until you have restored the balance. This time you may, if you want, make the final zero balance by changing the current in the fixed coil.

Record the value of the currents, the distance between the two wires, and the weights added.

Turn off the currents, and carefully remove the balance loop by sliding it out of the holding clips. Measure the length of the loop wire. But think carefully; what "length" do we mean? Review in your mind the results of the earlier demonstration.

Insert a shorter loop. Adjust it so that it is level with the fixed coil and so that the distance between loop and coil is just the same as you had before. This is important. The loop must also be parallel to the fixed coil, both as you look down at the wires from above and as you look at them from the side. Reset the balance to maximum sensitivity. The sensitivity clip will be near the top of its rod for the longest loop, near the bottom for the shortest one.

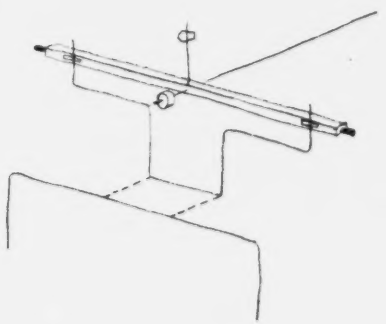


Fig. 3

Use the zero adjustment cylinder to reset the balance with no current—and no weights added. Use the indicator to mark the zero position. Now turn on both currents; check them to make sure that they are just the same as before.

Experiments

Add weights to the pointer notch until you restore balance. Turn off the current. Record the weights. Remove this loop, measure and record its length.

Repeat the above process for the other loops.

Results

Q11 Can you find the relationship between the length of the loop and the force on it? One way to do this, of course, is to make a plot of force against length. Try it.

Q12 If the force on the balance loop is F, what is the force on the fixed coil?

Q13 Can you see how to convert the force as measured in centimeters of wire hung on the pointer arm into the conventional units, newtons?

For class discussion

Be prepared to report the results of your particular investigation to the rest of the class. As a class you will be able to combine the individual experiments into a single statement about how the force varies with current, with distance and with length.

Q14 What other fact do you need to make this statement into an equation which would enable you to predict the force (in newtons) existing between the currents in two wires of given length and separation?

EXPERIMENT 36 Currents, Magnets and Forces

In Experiment 35 you found how the force between two wires depends on the current in them, their length and the distance between them. You also know that a nearby magnet exerts a force on a current-carrying wire. In this experiment different groups of students will investigate different aspects of the current-magnet interaction. You will again use the current balance, to do one of the three experiments described below. You may need to refer back to the notes on Experiment 35 for details on the equipment.

In this experiment you will not use the fixed coil. The frame on which the coil is wound will serve merely as a convenient support for the balance and the magnets.

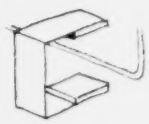
Attach the longest of the balance loops to the pivotal horizontal bar.

Connect the balance loop through an ammeter and rheostat to the 6-volt dc power supply.*

Do only one of the three alternative experiments (A, B and C) below. Then go on to read the last paragraph, "For Class Discussion."

A. Force between current and magnet, and how it depends on the current in the wire

1. Place two small ceramic magnets on the inside of the iron yoke. Their orientation is important; they must be turned so that the two near faces attract each other when they are moved close together. (Careful: ceramic magnets are brittle. They break if you drop them!) Place the yoke-plus-magnets unit on the platform so that the balance loop passes through the center of the region between the ceramic magnets.



2. Turn on the current. If nothing happens, check that there is current in the circuit, and that the magnets are placed correctly.

You will measure the force on the loop by finding what force (weight of wire) is needed to return it to its original position. This means that the horizontal pointer must move UP when you turn on the current. If the pointer moves down when you turn on the current, try to change something (the current? the magnets?) so that it does swing up.

3. Turn off the current. Check the zero position of the pointer arm and mark it with the indicator.

4. Turn on the current and adjust it to about one amp. Hang weights (wire hooks) on the notch in the pointer arm to return the pointer to the zero mark. You can make the final adjustment either by changing the length of wire on the notch or by adjusting the current in the loop. Record the weight (length of wire) added and the current which return the pointer to the zero mark.

5. Change the current to a different value, and add or subtract weights until you get a new balance. Record the force F and the current I_b.

6. Repeat the process until you have a reasonable number of sets of values (three is too few, and you probably won't have time for as many as ten).

*A Variac can be used instead of the rheostat to control current. Connect the balance loop through an ammeter to the power supply. Plug the power supply into the Variac, and the Variac into the 115 volt electrical outlet. By changing the setting of the Variac, you can adjust the current in the balance loop.

Results

Q1 What is the relationship between the magnitude of the current I_b and the resulting force F that the magnet exerts on the wire? (Try a plot.)

Q2 If the magnet exerts a force on the current, do you think the current exerts a force on the magnet? How would you test this?

Q3 Suppose you repeated your investigation with a different pair of magnets—a "stronger" or a "weaker" pair, or that you used the same pair of magnets but changed the separation between them. How would these changes affect the force on the current? Can you express the relationship between force, current and "strength" of the magnet in symbols?

If you have time, try the experiment with different magnets or with a different spacing between the two magnets of a pair. Plot F against I_b.

Q4 How do the two plots, obtained using different magnets, compare?

B. A study of the force between a magnet and current, and how it depends on the length of the region of interaction

1. Place two small ceramic magnets on the inside of the iron yoke. (Careful: ceramic magnets are brittle. They break if you drop them!) It is important to position them correctly: the two magnets should attract each other when they are moved close together.

Place the yoke in position on the platform so that the balance loop passes through the center of the magnetic system.

2. Turn on the current. If nothing happens, check that there is current in the circuit, and that the magnets are placed correctly. The pointer should move UP when you turn on the current; if it moves down, try to change something (the current? the magnets?) so that the pointer does swing up.

3. Turn off the current. When the pointer comes to rest, mark the zero position of the pointer with the indicator.

4. Turn on the current. Hang weights on the notch, say ten or fifteen centimeters of wire, and adjust the current to restore balance. Record the current and the length (weight) of wire.

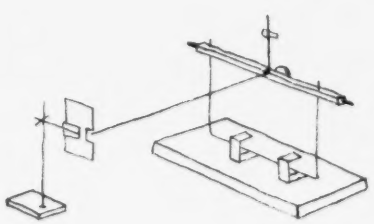
5. Remove that magnet-pair and set it aside; you will need it later.

6. Make another magnet-pair, put it in position, and check to see whether the balance is restored. You have changed neither the current nor the length of wire hanging on the pointer. If balance is restored, then this pair is acting just like the first one, and hence must be of the same strength.

7. If the second magnet does not turn out to be just as strong as the first, try other combinations of magnets until you have two units of the same strength. If possible, try to get three matched magnet-pairs.

8. Now place two of the magnet units on the platform at the same time. They should be at least 10 cm apart. Of course each unit must be positioned so that the pointer is deflected upward.

9. Check that the current is just what it was before, and then hang more or fewer weights until the balance is restored.



10. If you have three magnet units, repeat the above process using three units at a time. Again, keep the units well apart.

Results

Your problem is to find a relationship between the length of the region of interaction ℓ and the force F on the wire.

You may not know the exact length of the region of interaction between magnet and wire for a single unit. It certainly extends beyond the region directly between the two magnets. But the force decreases with distance from the magnets. As long as the separate units are far from each other, neither will be influenced by the presence of the other. The force due to each magnet will be the same as it would be if it were the only one present. You can then assume that the total length of interaction with two units is double that for one unit.

Q5 How does F depend on ℓ?

C. A study of the interaction between the earth and an electric current

1. Set the balance to maximum sensitivity by sliding the sensitivity clip to the top of the vertical rod and, if necessary, add a second clip. (But don't increase sensitivity so much that the balance flops over.)

2. With no current in the longest balance loop, align the zero mark with the end of the pointer arm.

3. Turn on the current and increase it to about 5 amps. Turn off the current and let the balance come to rest.

4. Turn on the current, and observe carefully: does the balance move when you turn the current on? Since there is no current in the fixed coil, and there are no magnets nearby, any force acting on the current in the loop must be due to an interaction between it and the earth's magnetic field.

5. To make measurements of the force on the loop, you must set up the experiment so that the pointer swings UP when you turn on the current. If the pointer moves down, try to find a way to make it go up. If you have trouble, consult your instructor. Turn off the current, and bring the balance to rest. Mark the zero position with the indicator.

6. Turn on the current. Hang weights on the notch, and adjust the current to restore balance. Record the current and the length of wire on the notch. Repeat the measurement of the force needed to restore balance for several different values of current.

If you have time, repeat your measurements of force and current for another (shorter) loop.

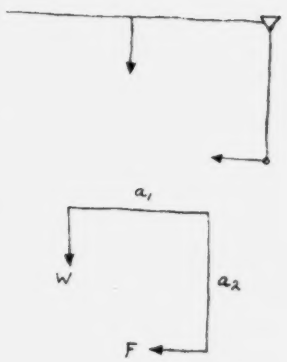
Results

Try to find the relationship between the current in the balance loop I_b, and the force F on it. Make a plot of F against I_b.

To measure the interaction in useful terms, we must express the force in the conventional units, newtons. To do this, you must first find the mass of the wire in grams, and then convert this mass into force in newtons. (Remember, the weight of a 1 kg mass is 9.8 newtons.)

The equipment acts like a seesaw or lever except that it has a right-angle bend in the center. Measure the length of the two arms (pivot to loop and pivot to notch).

Q6 What is the relationship between the two forces (weight of wire, force on current) when the system is balanced?



For class discussion

Different members of the class have investigated how force F varies with current I_b and with the length of the region of interaction with the current, ℓ. It is also clear that in any statement that describes the force on a current due to a magnet, we must include another term that takes account of the "strength" of the magnet.

Be prepared to report to the class on the results of your own investigations and to help formulate an expression that includes all the relevant factors investigated by different members of the class.

Q7 To compare the "strengths" of different magnets, we may compare the force exerted on a wire carrying 1 amp when the length of the wire interacting with the magnet is 1 meter. Can you express the "strength" of your magnet, or of the earth's interaction with the current, in these units? What force would the earth exert on a horizontal wire 1 meter long carrying a current of 1 amp?

Q8 In this experiment you have measured a vertical magnetic field—either that due to the two permanent magnets or the vertical component of the earth's magnetic field. How would you have to change the experiment to measure the horizontal component?

EXPERIMENT 37 Electron Beam Tube

If you did Experiment 34 (Electric Forces II—Coulomb's law) you found that the force on a test charge, in the vicinity of a second charged body, decreases rapidly as the distance between the two charged bodies is increased. In other words the electric field due to a single charged body decreases with distance from the body (Fig. 1a).

In many experiments it is useful to have a region where the field is uniform, that is, a region where the force on a test charge is the same at all points. The field between two parallel, flat, oppositely charged plates is uniform (Fig. 1b).

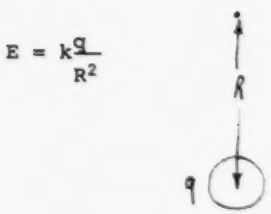


Fig. 1(a) The field at a distance R from a charge q is $E = k\frac{q}{R^2}$.

Fig. 1(b) The field between two parallel flat plates is uniform. $E = \frac{V}{d}$, where V is the potential difference (volts) between the two plates.

In Experiments 35 and 36 (The Current Balance), you measured the force which is experienced by moving charges, i.e., currents, when they are in the vicinity of other currents or of magnets. You found that there is a force on a current in a magnetic field.

"Free" charges

In this experiment you can re-examine the effects of electric and magnetic fields on moving electric charges. But there is one important difference: this time the charges will not be confined to a pithball or to a metallic conductor. Instead they will be "free" charges—free to move on their own in air at low pressure.

How do we get such free charges? You may have seen a demonstration in which electric charge was freed from a heated filament in a vacuum tube. For example, in one demonstration of this type the response of a charged electroscope connected to a metal plate in the vacuum tube suggests that charges have moved across the tube from the hot filament to the plate. Only a positively charged electroscope can be discharged in this way, and from this it is inferred that negative charges (electrons) are freed from the hot filament and cross to the plate.

But it would be difficult, using that vacuum tube, to see just what are the effects of electric and magnetic fields on moving electrons, because we have no easy way of knowing where they are inside the tube or which way they are moving. Instead, you will build a special tube of your own for this experiment. In this tube there is a small hole in the plate, and some of the electrons emitted from the filament pass through this hole into the space beyond. It is quite easy to observe how their motion is affected by electric and magnetic fields after they have passed through the hole.

When one of the air molecules that remain in the partially evacuated tube is struck by an electron, the molecule

emits some light. The light from mercury and sodium vapor lamps comes from molecules excited by electron collisions. Molecules of different gases emit light of different colors.

Building your tube

Full instructions on how to build your tube are included with the parts. Note that only one of the plates (the anode plate) is connected to the anode cap. The other plate (deflection plate) must not touch the anode cap. Be careful to line up the filament directly behind the hole in the plate (anode cap).

You can see how good the alignment is if you look in through the narrow glass tube, after you have assembled the filament and plates on the header. You should be able to see the filament across the center of the hole in the cap. Don't apply the sealant until you have checked this alignment. Leave the tube undisturbed overnight while the sealant hardens.

Operating your tube

Connect your tube as shown in Fig. 2. The low voltage power supply provides current to heat the filament and make it emit electrons. The batteries, or high voltage power supply, provide the accelerating voltage to draw these electrons toward the anode. Let your instructor check your circuit before you proceed further.

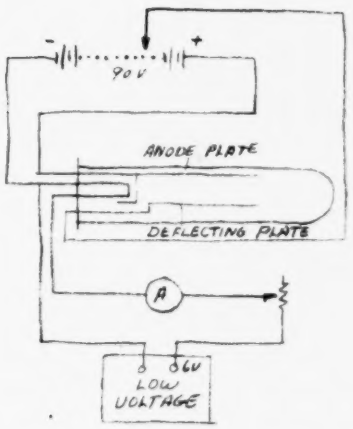


Fig. 2

If you have done a good job putting your tube together, and are using a reasonably good vacuum pump, you should not have much difficulty in getting a glow in the region where the electron beam comes through the hole in the plate.

When you get an electron beam, try to deflect it in an electric field: apply potential differences of + and -50 volts between the anode and the deflecting plate (see Fig. 3).

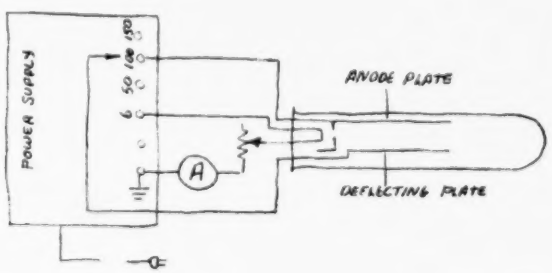


Fig. 3

Q1 Make a sketch showing the direction of the electric field and of the force on the charged beam. Does the deflection in the electric field confirm that the beam consists of negatively charged particles?

To obtain a magnetic field use the yoke and magnets from the current balance experiment.

Q2 Make a sketch showing the relative orientation of the magnetic field, the velocity of the electrons and the force on them.

Q3 How would you have to orient the magnets to permit the charges to travel straight through the tube, cancelling the effect of an electric field between the two plates?

An important question

One of the questions facing physicists at the end of the nineteenth century was to decide the nature of these "cathode rays" (so-called because they are emitted from the negative electrode or cathode). One group of scientists (mostly Germans) thought that cathode rays were a form of radiation, like light, while others (mostly English) thought they were streams of particles. J. J. Thomson did experiments much like the one described here that showed that the cathode rays were in fact made of particles, the particles we call electrons.

These experiments were of great importance in the early development of atomic physics. In Unit 5 we will return to this topic and you will be able to do an experiment to determine the ratio of the charge of an electron to its mass.

In the activities for Chapter 14 of this handbook you will find some suggestions for building other kinds of electron tubes, like the ones that were used in radios before the invention of the transistor.

ACTIVITY Detecting electric fields

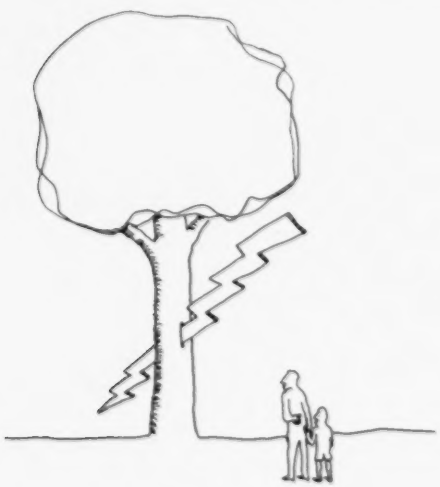
There are many methods that can be used to explore the shape of electric fields:

1. Gilbert's versorium. A sensitive electric "compass" is easily constructed from a toothpick, a needle and a cork. The forces on the induced surface charges of the toothpick cause the toothpick to line up along the direction of the field.

To construct the versorium, first bend a flat toothpick into a slight arc. This will give it stability by lowering its center of gravity below the pivot point. Stick a needle, sharp end up, into a cork; this is the support. Locate the balance point of the toothpick and drill a hole, using a nail, almost all the way through the pick. (For details of Gilbert's and other experiments, see Holton and Roller, Foundations of Modern Physical Science, Chapter 26.

2. Suspend a charged pithball from a stick on a thin insulating thread, and use it as a roughly quantitative indicator of fields around charged spheres, plates and wires.

Use a point light source to project a shadow of the thread and ball. The angle between the thread and the vertical gives a rough measure of the forces. Show the uniformity of the field near a large plate suspended by tape strips, and the 1/r drop-off of the field near a long charged wire, hung over a wooden rod.



To prevent leakage of charge from the pointed ends of a charged wire, fit the ends with small metal spheres. Even a smooth small blob of solder at the ends should help.

Plastic strips rubbed with cloth are adequate for charging well-insulated spheres, plates, or wires.

ACTIVITY Voltaic pile

Cut twenty or more discs of each of two different metals. Copper and zinc make a good combination. (The round metal "slugs" from electrical outlet box installations can be used for zinc discs because of their heavy zinc coating.) Cut pieces of filter paper or paper towel to fit in between each pair of two metals in contact. Make a pile of the metal discs and salt-water soaked paper, as Volta did. Keep them in order; for example, copper-paper-zinc, copper-paper-zinc, etc. Connect copper wires to the top and bottom ends of the pile. Touch the free ends of the wires with two fingers on one hand. Can you increase the effect by moistening your fingers? Can you increase the effect by attaching metal strips or plates to the top and bottom discs? In what other ways can you increase the effect? How many discs do you need in order to light a flashlight bulb? If you have metal fillings in your teeth, try biting a piece of aluminum foil. Can you explain the sensation? (Adapted from History of Science Cases for High Schools, Leo E. Klopfer, Science Research Associates, 1966.)

ACTIVITY An 11¢ battery

Using a penny (95 per cent copper) and a dime (90 per cent silver) you can make an 11¢ battery. Cut a one-inch square of filter paper or paper towel, dip it in salt solution, and place it between the penny and the dime. Connect the penny and the dime to the terminals of a galvanometer with two lengths of copper wire. Does your meter indicate a current? Will the battery also produce a current with the penny and dime in direct (dry) contact and the moistened filter paper on one side?

ACTIVITY Force law for bar magnets

The diagram in Fig. 1 shows a setup which you can use to determine how force varies with distance away from a bar magnet, much as you determined the force law between charged objects in Experiment 34, Coulomb's Law.

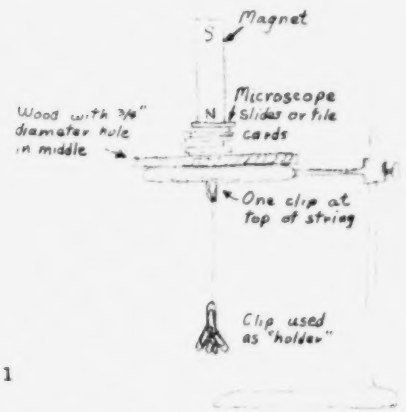


Fig. 1

Procedure

Drill or cut a 3/4"-diameter hole in a piece of wood or heavy cardboard to use as a support for the microscope slides (or 3 × 5 file cards). Place a few slides on the wood support. Stand the magnet on top. (Always use the same end of the bar magnet, as the top paper clip tends to be slightly magnetized. Tape enough magnets together to give a field strong enough to support one clip at a distance of ten slides. The 6" string keeps the other clips out of the strongest part of the field, so they serve only as "weights.")

Bring the top clip (and string) up under the board. It will be held against the slides under the board if there aren't too many slides. Continue adding slides until the clip is just NOT held up. (Cover glasses for microscope slides, some of which have 1/10 the thickness of a single slide, can be used for fine adjustment of the distance.)

Record "1 clip," and the number of slides. Then tie another clip to the bottom of the string, and remove slides until the string and two clips are just NOT supported. Continue adding clips, reducing the number of slides, and taking data.

You found in Experiment 34 that the force between two charged objects varies as $1/d^2$. Perhaps the force near a bar magnet also varies as $1/d^2$. Plot a graph of force vs. $1/d^2$, where d is the total thickness of slides for a given number of clips. If you wish, you may convert number of slides into millimeters. Try force vs. $1/d$ and $1/d^3$, too, if $1/d^2$ isn't a straight line.

Problem

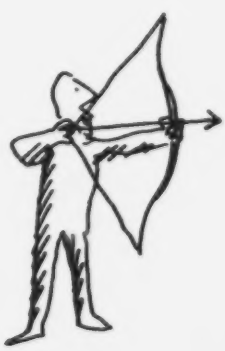
So far we have assumed that the "distance" between the magnet and the top clip

is simply the total thickness of the slides. This assumes that the "pole" of the magnet is located at the very end of the magnet; in Experiment 34 we assumed that we could pretend all the charge was located at the center of the sphere. For the bar magnet the "effective" pole is somewhere inside the end of the magnet. To find out what this correction on d should be we must resort to some algebra.

If the force is an inverse-square force then

$$F_1 \, d_1^2 = F_2 \, d_2^2$$

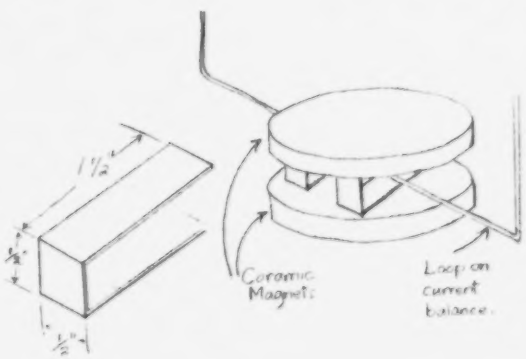
for any distances d_1 and d_2 from the "pole center." If the effective pole is a distance x inside the end of the magnet, then the distances d_1 and d_2 are equal to the measured distances, d_1' and d_2', plus x. So $F_1(d_1' + x)^2 = F_2(d_2' + x)^2$. Choose two sets of your values for F_1, d_1, F_2 and d_2, substitute them in the equation above, and solve the resulting quadratic equation for x. Then correct all your values for d by adding x to each of them. Again plot F vs. $1/d^2$, which should be much better than the first graph you made. (Adapted from "Illustrating the Inverse Square Law with a Bar Magnet," Walter Ainsworth, School Science and Mathematics, October, 1963.)

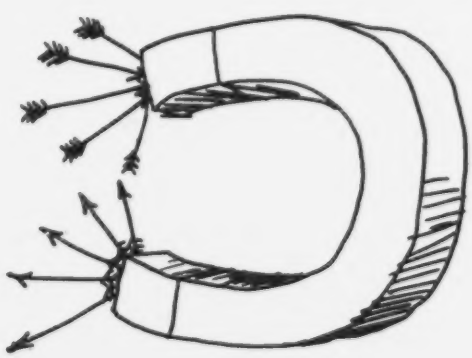


ACTIVITY **Measuring magnetic field intensity**

Many important devices used in physics experiments make use of a uniform magnetic field of known intensity. Cyclotrons, bubble chambers and mass spectrometers are examples. You can use the current balance described in Experiments 35 and 36 to measure the magnetic field intensity in the space between the pole faces of two ceramic disc magnets placed close together. Then when you are learning about radioactivity in Unit 6, you can observe the deflection of beta particles as they pass through this space, and determine the average energy of the particles.

Bend two strips of thin sheet aluminum or copper (not iron), and tape them to two disc magnets as shown in the drawing below:





Be sure that the pole faces are parallel and are attracting each other (unlike poles facing each other). Suspend the movable loop of the current balance midway between the pole faces and determine the force needed to restore the balance to its initial position when a measured current is passed through the loop. You learned in Experiment 36 that there is a simple relationship between the magnetic field intensity, the length of the part of the loop which is in the field, and the current in the loop. It is $F = BI\ell$, where F is the force on the loop in newtons, B is the magnetic field intensity in teslas, I the current in amperes, and ℓ the length of the part of the current-carrying loop which is actually in the field. With your current balance, you can measure F, I and ℓ and thus compute B.

For this activity we make two simplifying assumptions which are not strictly true but which enable us to obtain reasonably good values for B: (1) the field is fairly uniform throughout the space between the poles, and (2) the field drops to zero outside this space. With these approximations we can use the diameter of the magnets as the quantity ℓ in the above expression.

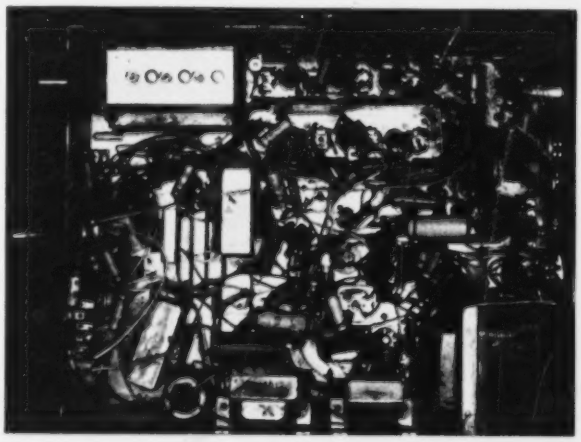
Try the same experiment with two disc magnets above and two below the loop. How does B change? Bend metal strips of different shapes so you can vary the distance between pole faces. How does this affect B?

An older unit of magnetic field intensity which is still often used is the gauss. To convert from one unit to the other, use the conversion factor 1 tesla = 10^4 gauss. (1 tesla is also often expressed as 1 weber/m^2.)

Save your records from this activity so you can use the same magnets for measuring beta deflection in Unit 6.

ACTIVITY Who's who in TV

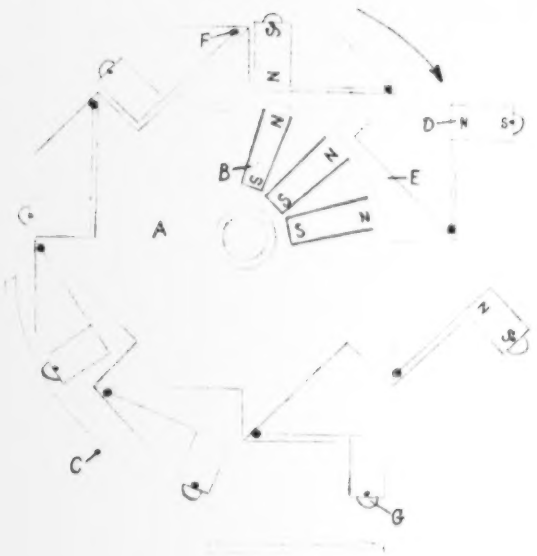
A photo of the bottom of a TV set is shown below. Refer to the photo of different types of capacitors on page 54 of the text, and see how many of each kind you can spot in the photo. How many transformers can you identify? Resistors are shown on page 60 of the Unit 4 text. Can you spot them?



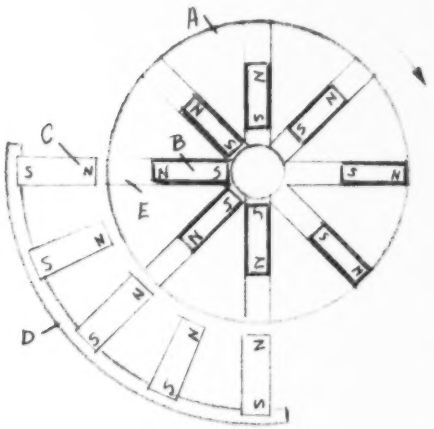
The similarity of many modern capacitors to Leyden jars isn't obvious. Carefully take apart several of the and types to see the pair of conducting surfaces separated by an insulator. (Many "can" types use thin chemical layers instead of strip metal foil and insulator. These are wet and should be left alone.)

ACTIVITY More perpetual motion machines

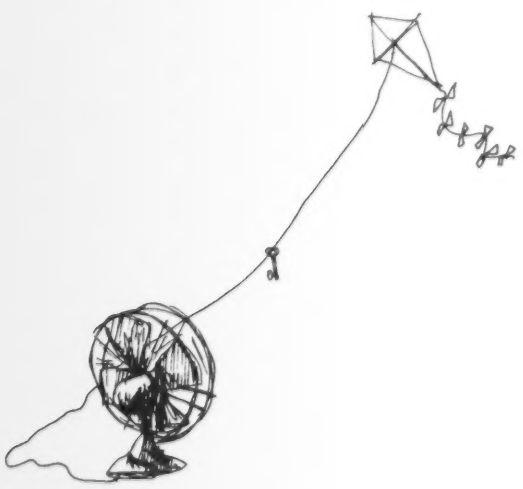
The two diagrams on the next page show two more of the perpetual motion machines discussed by S. Raymond Smedile in his book, Perpetual Motion and Modern Research for Cheap Power. (See also page 60 of the Unit 3 Student Handbook.) What is the weakness with the argument for each of them? Also see "Perpetual Motion Machines," Stanley W. Angrist, Scientific American, January, 1968.



NUMBER 14 represents a stationary wheel A around which is a larger movable wheel E. On the stationary wheel A are placed three magnets marked B in the position as shown in the drawing. On the rotary wheel E are placed twelve magnets marked D that are attached to twelve levers and securely hinged to wheel E at point marked F. Each magnet is also provided with a roller wheel G so as to prevent friction as it rolls on the guide marked C. The guide C is supposed to push each magnet towards the hub of this mechanism as it is being carried upward on the left hand side of the mechanism where it will roll over the top and down into the right where it will repel the magnet facing it and cause the magnet on the wheel marked E to fall over, creating an overbalance of weight on the right of wheel E and thus rotating perpetually in a clockwise direction.



NUMBER 15 represents a wheel A in which are placed eight hollow tubes marked E. In each of the tubes is inserted a magnet B so that it will slide back and forth. Figure D represents a stationary rack in which are anchored five magnets as shown in the drawing, each magnet is placed so that it will repel the magnets in wheel A as it rotates in a clockwise direction. Since the magnets in stationary rack D will repel those in rotary wheel A in the manner shown in the drawing, this will cause a perpetual overbalance of magnet weight on the right side of wheel A.



ACTIVITY Additional Activities Using the Electron Beam Tube

1. Focusing of electron beam

A current in a wire wrapped around the electron tube will produce a magnetic field parallel to the axis of the tube. An electron moving along the axis will experience no force—its velocity and the magnetic field are parallel. But for an electron moving perpendicular to the axis, the field is perpendicular to its velocity—it will therefore experience a force (F = Bqv) at right angles to both velocity and field. As we know, a force on a particle always perpendicular to its velocity produces a circular orbit ($F = \frac{mv^2}{R} = Bqv$).

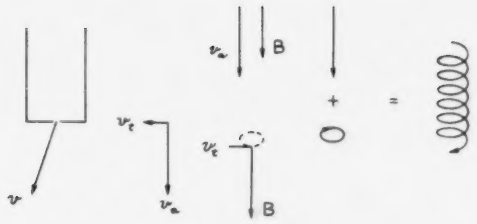
Suppose the electron is moving down the tube only slightly off axis, in the presence of an axial field. The electron's velocity can be thought of as made up of two components: an axial one (v_a) and a transverse one (v_t). Consider these two components of the electron's velocity independently. We know that the axial one will be unaffected—the electron will continue to move down the tube with velocity v_a. The transverse velocity, however, is perpendicular to the field, and so the electron will move in a circle. The equation of motion is

$$m \frac{v_t^2}{R} = Bqv_t ,$$

and the radius of the circle is therefore

$$R = \frac{m}{q} \frac{v_t}{B} .$$

The resultant motion—uniform velocity down the axis plus circular motion perpendicular to the axis—is a helix (like the thread on a bolt).



In the absence of any field, electrons traveling off-axis would continue towards the edge of the tube. In the presence of an axial field, however, they move down the tube in a helix—they have been "focused" into a beam. The radius of this beam depends on the field strength B and the transverse velocity v_t.

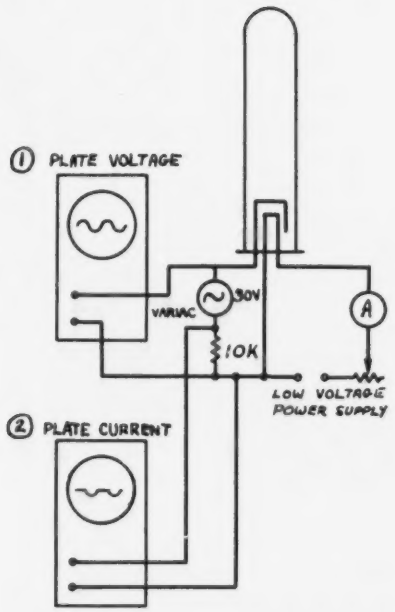
Wrap heavy gauge copper wire (e.g., #18) around the tube (about two turns per centimeter) and connect it to a low voltage, high current source to give appreciable focusing. Observe the shape of the fluorescent area using different coils and currents. Alternatively, you can use ring magnets slipped over the tube to produce the axial field.

2. Diode and triode characteristics

These experiments are performed at anode voltages below those that cause ionization (a visible glow) in the tube.

a) Rectification

Connect an ammeter in the plate circuit to show the direction of the conventional current, and to show that there is a current only when the plate is at a higher potential than the filament. Note that there is a measurable current at voltages far below those needed to give a visible glow in the tube. Then apply an alternating potential difference between plate and filament (e.g., from a Variac). Use an oscilloscope to show that the plate is alternately above and below filament potential. Then connect the oscilloscope across a resistor in the plate circuit to show that the current is only in one direction.

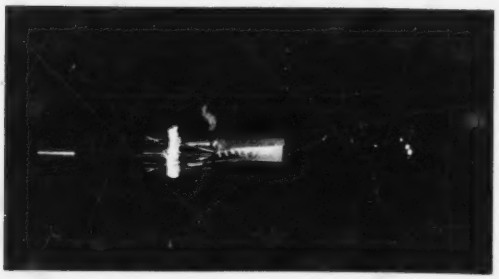


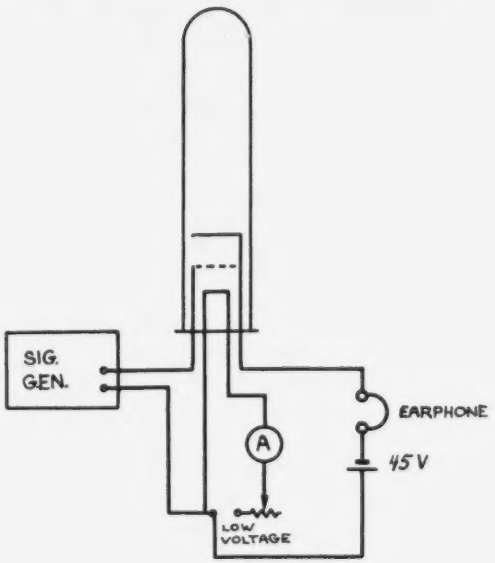
It is interesting to plot graphs of plate current versus filament current, and plate current versus plate voltage. Note that these characteristic curves apply to voltages too low to produce an ionization.

b) Triode

The "triode" illustrated was made using thin aluminum sheet for the plate and nichrome wire for the grid. The filament is the original one from the electron-beam tube kit, and thin aluminum tubing from a hoppy shop was used for the connections to plate and grid.

Again, you can plot curves showing triode characteristics: plate current against grid voltage, plate current against plate voltage. You can also calculate the amplification factor: [$\mu = -(\Delta v_{plate}/\Delta v_{grid})$ for constant plate current]. (Change the grid voltage by a small amount, then adjust the plate voltage until you have regained the original plate current. The magnitude of the ratio of these two voltage changes is the amplification factor.) The tube gave noticeable amplification in the circuit shown below.





An Isolated North Magnetic Pole (?)

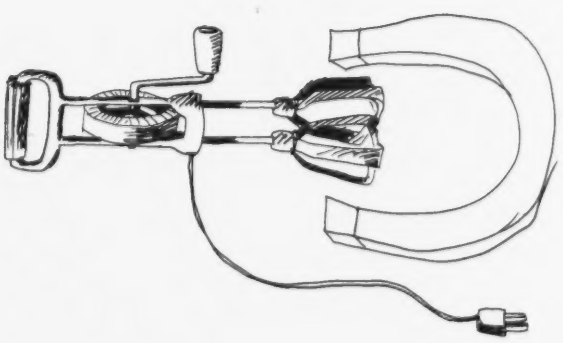
Available in some hardware stores are magnets made of a rather soft rubber-like substance. (These are supplied by Jiffy, Inc., 144 N. 13 Street, Philadelphia, Pa., 19107.) They are flat pieces 20 mm × 25 mm and about 5 mm thick, magnetized north pole on one 20 × 25 mm surface and south pole on the other. They may be cut with a sharp knife.

Suppose we cut six of these so that we have six square pieces 20 mm on the edge and then bevel the edges on the S side of each piece so that the pieces can be fitted together to form a hollow cube with all the N sides facing outward. The pieces repel each other strongly and may be either glued (with rubber cement) or tied together with thread.

Do we now have an isolated north pole—that is, a north pole all over the outside (and south pole on the inside)?

Is there a magnetic field directed outward from all surfaces of the cube?

Reprinted from The Physics Teacher, March, 1966.



ACTIVITY Faraday disc dynamo

You can easily build a disc dynamo similar to that shown at the bottom of page 82 in the Unit 4 text.

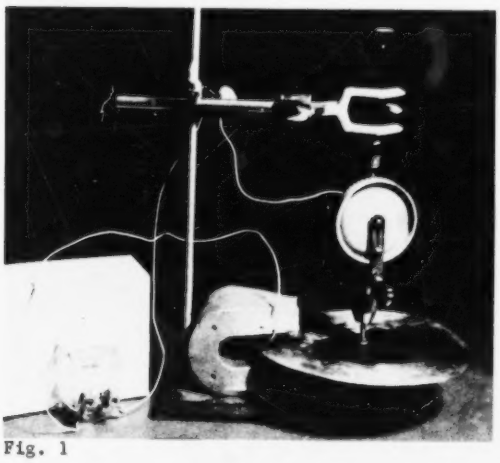


Fig. 1

Cut an 8" diameter disc of sheet copper. Drill a hole in the center of the disc, stick a bolt through the disc and run a nut up tight against the disc so the disc will not slip on the bolt. Chuck the bolt in a hand drill. Clamp the drill in a ringstand so the disc passes through the region between the poles of a large magnet. Connect one lead of a 100 micro-amp dc meter to the metal part of the drill which doesn't turn. Tape the other lead to the magnet so it brushes against the copper disc as the disc is spun between the magnet poles.

Frantic cranking can create a 10 micro-amp current with the magnetron magnet shown in Fig. 1. When we used one of the metal yokes from the current balance, with three ceramic magnets on each side of the yoke, we were just able to get the needle to noticeably move from the zero position.

The braking effect of eddy currents in the disc can also be noticed. Remove the meter and leads. Remove the magnet. Have one person crank while another brings the magnet up to the position where the disc is spinning between the magnet poles. Compare the effort needed to turn the disc with and without the magnet over the disc. If the disc will coast, compare the coasting time with and without the magnet in place.

ACTIVITY Generator jump-rope

With a piece of insulated wire about twice the length of a room, and a sensitive galvanometer, you can generate an electric current using only the earth's magnetic field.

Connect the two ends of the wire to the meter. Then two people whirl one of the wires like a jump-rope. As the wire cuts across the earth's magnetic field, a current is generated. If you do not have a sensitive meter available, connect the wire to the input of one of the amplifiers, then connect the amplifier to a less sensitive meter.

Questions:

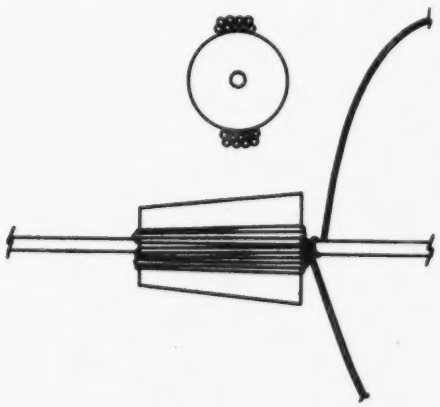
How does the current generated when the people stand in a north-south line compare with that generated with the same motion along an east-west line? What does this tell you about the earth's magnetic field? Is there any effect when the people stand on two landings and hang the wire down a stairwell while swinging it?

ACTIVITY **Simple meters and motors**

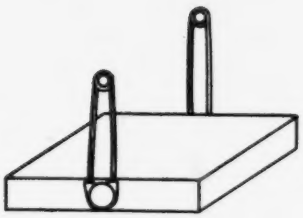
You can make simple current meters and motors from very simple parts:

- 2 ceramic magnets, 1 steel yoke } from current balance kit
- 1 no. 7 cork
- 1 metal rod, about 1/16 inch diameter and 5 inches long (a piece of bicycle spoke, coat hanger wire, or a large finishing nail will do)
- 1 block of wood, about 4" × 2" × 1/2"
- About 3 meters of no. 30 copper magnet wire
- 2 thumb tacks
- 2 safety pins
- 2 carpet tacks or small nails
- 1 white card card 4" × 5", stiff black paper, for pointer } for meter only
- electrical insulating tape (for motor only)

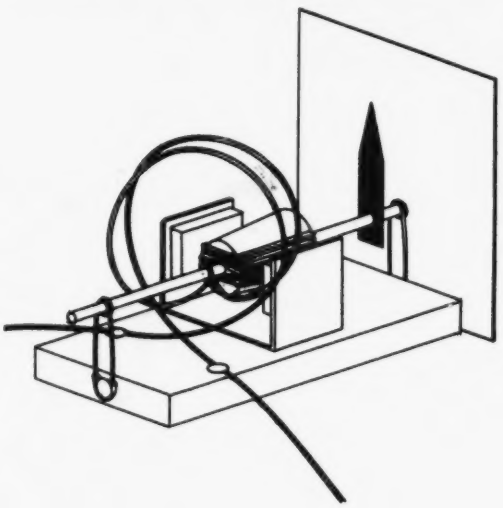
The steps are outlined in these sketches:



Push rod through cork. Wind armature of about 20 turns around cork, keeping turns parallel to rod. Leave about 30 cm of wire at both ends.



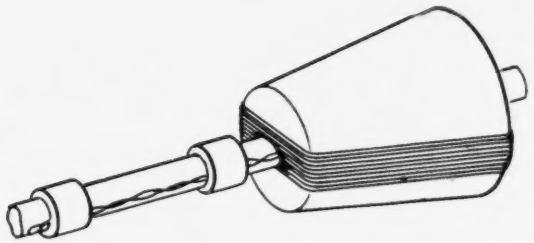
Use nails or carpet tacks to fix safety pins to wooden base block.



Make a pointer out of the black paper, push it on to the metal rod. Pin a piece of white card to one end of the base. Suspend the armature between the two safety pins. Form free ends of wire into two loose coils and attach to base with thumb tacks. Put the two ceramic magnets on the ⊔ shaped yoke (unlike poles facing), and place yoke around armature.

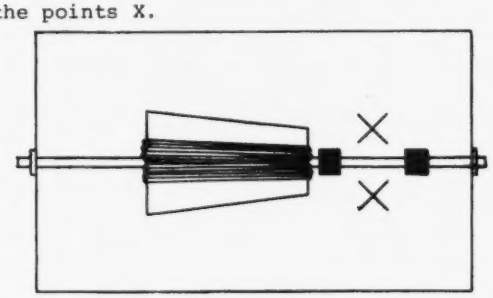
Connect leads (clean off insulation first!) to dc source (a large 1.5 volt cell). You may want to include a rheostat to vary the current.

To make a motor wind an armature as for the motor. Leave about 6 cm of wire at each end, bend each into a loop and twist into a pigtail. Tape the two pigtails to the metal rod. Carefully scrape the enamel off the pigtail:

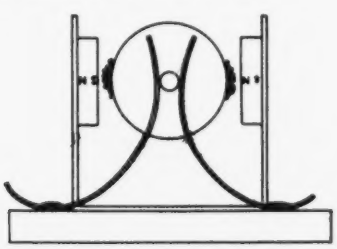


Fix the two safety pins to the base as for the meter. Mount the coil between the safety pins.

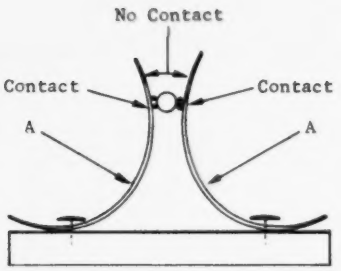
The current leads into the motor are made from two pieces of wire, attached to the base board with thumb tacks, at the points X.



Place the magnet yoke around the coil. The coil should spin freely.



Connect a 1.5 v battery to the leads. The motor should start when spun. If it does not, check the contacts between leads and pigtails. You may not have removed all the enamel from the wires. Try pressing lightly at the points A to improve the contact.



ACTIVITY **Simple motor-generator demonstration**

With two U-magnets and two coils which you wind yourself you can prepare a simple demonstration showing the principles of a motor and a generator.

Wind two flat coils of 100 turns each of magnet wire. The cardboard tube from paper towels makes a good form. Leave about 2 feet of wire free at each end of the coil. Tape the coil so it doesn't unwind when you remove it from the cardboard tube.

Hang the coils from two supports as shown in Fig. 1 so they pass over the poles of two U-magnets set on the table.

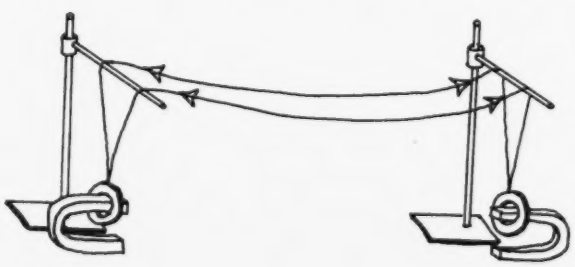


Fig. 1

Connect the coils together. Pull one coil to one side and release it. What happens to the other coil? Why? Does the same thing happen if the coils are not connected to each other? If the magnets are reversed?

Try various other changes, such as turning one of the magnets over while

both coils are swinging, or starting with both coils at rest, but sliding one of the magnets back and forth.

If you have a sensitive galvanometer, it is interesting to connect it between the two coils.

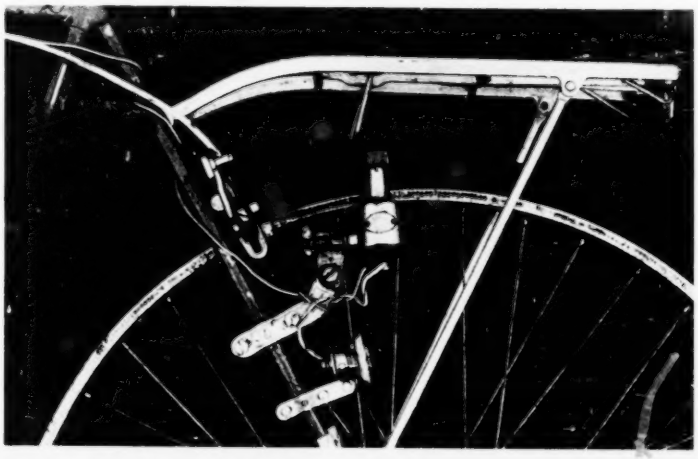
(Adapted from A Sourcebook for the Physical Sciences, Joseph and others, Harcourt, Brace and World, 1961, p. 529.)

ACTIVITY Physics collage

Many of the words we use in physics class enjoy wide usage in everyday language. Cut "physics words" out of magazines, newspapers, etc. and make your own collage. You may wish to formulate a more challenging art problem for yourself by trying to give a visual representation of a physical concept, such as speed, light, or waves. The Unit 1 Reader article, "Representation of Movement" may give you some initial inspiration.

ACTIVITY Bicycle generator

The generator on a bicycle operates on the same basic principle as that described in the text, but with a very different, and extremely simple, design. Take apart such a generator and see if you can explain how it works. Note: you probably won't be able to reassemble it.



2.

LAPIS POLARIS, MAGNES.

Lapis recluſit iſte Flauio abditum Poli ſuum hunc amorem, at ipse nautæ.

© BURNDY LIBRARY

THE LODESTONE, THE MAGNET—*That stone disclosed to Flavio its secret love for the pole, but he disclosed it to the sailor.*

The philosopher in his study is surrounded by the scientific equipment of his time. In the left foreground in a basin of water a natural magnet or lodestone, floating on a raft of wood, orients itself north and south. Traders from the great Mediterranean port of Amalfi probably introduced the floating compass, having learned of it from Arab mariners. An Amalfi historian, Flavius Blondus, writing about 1450, indicates the uncertain origin of the compass but later historians in repeating this early reference warped it and gave credit for the discovery of the compass to Flavius.

Can you locate the following items: galleon, armillary sphere, compass, octant, hourglass, celestial globe, pocket sun-dial, and a versorium.

EXPERIMENT 38 Waves, Modulation, Communication

Here are some suggestions for more investigations you can do with equipment that you have already seen demonstrated. Be sure you understand how to use the equipment. You may want to repeat for yourself some of the demonstrations you saw in class. Although different groups of students will use different equipment, all the investigations are related to the same phenomena—how we can communicate with waves.

A. Turntable oscillators

Turn on the oscillator with the pen attached to it. Turn on the chart recorder, but do not turn on the oscillator the recorder is mounted on. The pen will trace out a sine curve as it goes back and forth over the moving paper. When you have recorded a few inches, turn off the oscillator and bring the pen to rest in the middle of the paper. Now turn on the second oscillator, at the same rate that the first one was going. The pen will trace out a similar sine curve as the moving paper goes back and forth under it.

Q1 What do you predict will happen if you turn on <u>both</u> oscillators? Try it.

Look carefully at the two sine curves drawn by the two oscillators. The "wavelengths" of the two curves are probably very nearly, but not exactly, equal.

You can change the "wavelength" of one of the components slightly by putting weights on one of the platforms to slow it down a bit.

Q2 Do this and make more traces by adding other pairs of sine curves. A mathematical analysis shows that the "wavelength" of the envelope (λ_e in Fig. 1) will <u>increase</u> as the "wavelengths" of the two components (λ_1, λ_2) become more nearly equal. Do your curves confirm this?

Q3 If the two "wavelengths" were exactly equal, what pattern would you get when both turntables were turned on, that is, when the two sine curves were superposed? What else would the pattern depend on, as well as the "wavelengths?"

As λ_e gets bigger, the difference between λ_1 and λ_2 gets smaller. It is thus possible to detect a very small difference in the two wavelengths by examining the resultant wave for changes in amplitude that take place over a long distance. This method, called the method of beats, provides a sensitive way of comparing two oscillators, and of adjusting one until it has the same frequency as the other. This method is also used for tuning musical instruments. If you play the same note on two instruments that are not quite in tune, you can hear the beats. And the more nearly in tune the two are the slower the frequency of the beats.

Q4 In radio communication a signal can be transmitted by modulating a carrier wave (frequency f_c) at the frequency of the signal (f_s). A "snapshot" of the resultant wave looks just like the pattern you have been producing.

Fig. 1

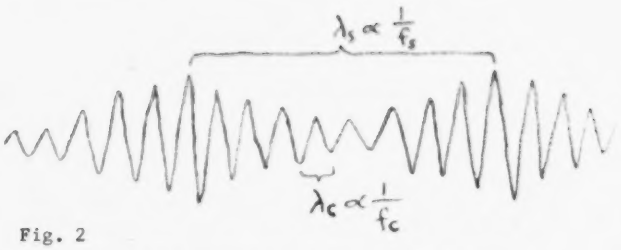


Fig. 2

Why must the carrier frequency be much greater than the signal frequency?

Q5 Why is a higher frequency needed to transmit television signals than radio signals? (The highest sound that we can hear has a frequency of about 12,000 cycles per second. The electron beam in a television tube completes one picture of 525 lines in $\frac{1}{30}$ of a second, and the intensity of the beam may have to vary many times during a single line scan.)

B. Resonant circuits

You have seen in a demonstration that to transmit a signal from one circuit to another the two circuits must be "tuned" to the same natural frequency. To investigate the range of frequencies obtainable with the circuit connect an antenna (length of wire) to the resonant circuit, amplifier and oscilloscope as shown in the diagram.

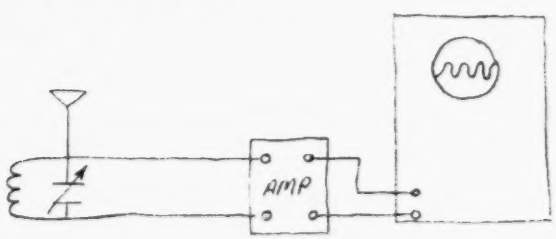


Fig. 3

Set the oscilloscope to "Internal Sync" and the sweep rate to about 100 kc/sec.

Q6 Change the setting of the variable capacitor and see how the trace on the oscilloscope changes. Which setting of the capacitor gives the highest frequency, which the lowest? By how much can you change the frequency by adjusting the capacitor setting?

When you tune a radio you usually are doing just the same thing: changing the setting of a variable capacitor to tune the circuit to a different frequency.

The coil also plays a part in determining the resonant frequency of the circuit. If it has a different number of turns, a different setting of the capacitor would be needed to get the same frequency. Another way in which the effect of the coil can be changed is by putting some iron inside it.

Q7 Does putting iron (e.g., a handful of 6-inch nails) inside the coil increase or decrease the resonant frequency of the circuit?

You have probably seen a demonstration of how one can transmit a signal from one tuned circuit to another. (If you have <u>not</u> seen the demonstration, you should set it up for yourself.)

Fig. 4

The two coils have to be quite close to each other for the "receiver" circuit to pick up the signal from the "transmitter."

Q8 Investigate the effect of changing the position of one of the coils. Try turning one of them round, moving it further away, etc.

Q9 What happens when you put a sheet of metal, plastic, wood, cardboard, glass, etc. between the two coils?

Q10 Why does an automobile always have an outside antenna, but a home radio does not?

Q11 Do you think it is possible to communicate with a submarine by radio?

C. Microwaves

The simplest way to measure the wavelength of microwaves is to set up standing waves and measure the distance between successive nodes:

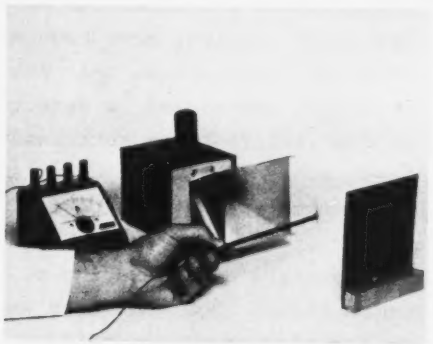


Fig. 5

Q12 What is the wavelength? Microwaves, like light, propagate at 3×10^8 m/sec. What is the frequency of the microwaves? Find microwaves in the chart of the electromagnetic spectrum given on p. 120 of Chapter 16. What names are given to radiation of somewhat longer, and somewhat shorter wavelength?

With microwaves it is easy to demonstrate interference between direct radiation from a source and radiation reflected from a flat surface, such as a sheet of metal.

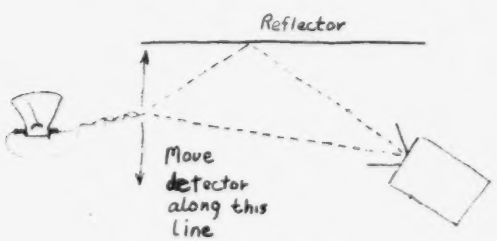


Fig. 6

If you move the detector along a line perpendicular to the reflector, you should pick up a series of maxima and minima.

You can also vary the signal at the detector by moving the reflector while keeping source and detector fixed. Try to find a position of the reflector for which the signal at the detector is zero.

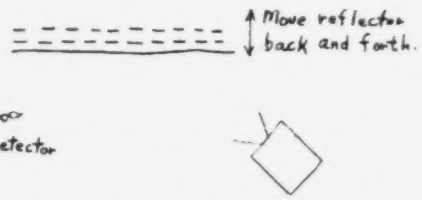


Fig. 7

What do you predict will happen when you remove the mirror? Try it.

This kind of interference also occurs with light waves, but because of their short wavelength it is much more difficult to demonstrate. The interference between direct and reflected radio waves has important practical considerations.

There is a shell of partly ionized (and therefore electrically conducting) gas that surrounds the earth roughly 300 kilometers above the earth's surface. Because this shell, called the ionosphere, is a good reflector for radio waves, it is used to send radio messages to points that, because of the curvature of the earth, are too far away to be reached directly.

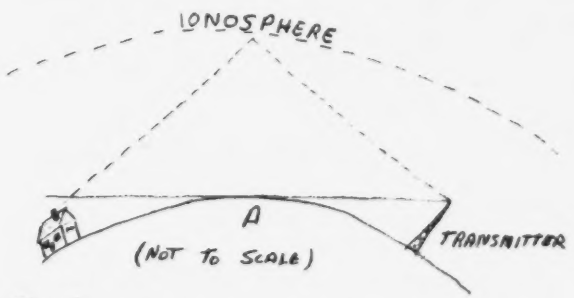


Fig. 8

If the transmitting tower is 100 meters high, then point A—the furthest point that the signal can reach directly in flat country—is 35 kilometers (about

20 miles) away. But by reflection from the ionosphere a signal can reach around the corner to B and beyond.

Sometimes both a direct and a reflected signal will arrive at the same place and interference occurs; if the two are out of phase, and have identical amplitudes the receiver will pick up nothing. Such destructive interference is responsible for radio fading. It is complicated by the fact that the height of the ionosphere and the intensity of reflection from it vary during the day with the amount of sunlight.

Also there can be multiple reflections—the radiation can bounce back and forth between earth and ionosphere several times on its way from say New York to Calcutta, India.

Microwaves of about 6-cm wavelength are used to transmit telephone conversations over long distances. Because microwave radiation has a limited range, a series of relay stations have been erected about 30 miles apart across the country. At each station the signal is detected and amplified before being retransmitted to the next one. If you are using a microwave generator that can be amplitude modulated at different frequencies, you can put together a demonstration of how this system works. You will need an oscillator (or microphone), amplifier, microwave generator and power supply, detector, amplifier and loud speaker.

ACTIVITY Inside a radio tube

Receiving tubes, such as those found in radio and TV sets, contain many interesting parts that illustrate important physical and chemical principles.

Choose a discarded tube. Your radio-TV serviceman will probably have some he can give you. Look up the tube number in a receiving tube manual, and, if possible, find a triode. Warning: do not attempt to open a TV picture tube!!!

Examine the tube, and notice how the internal parts are connected to the pins by means of wires located in the bottom of the tube. The glass-to-metal seal around the pins must maintain the high vacuum inside the tube. As the tube heats and cools, the pins and glass must expand together. An iron-nickel alloy is used for the pins whose coefficient of expansion is close to that of the glass. The pins are coated with red copper oxide to bond the metal to the glass.

The glass envelope was sealed to the glass base after the interior parts were assembled. Look at the base of the envelope and you can see where this seal was made. After assembly, air was drawn from the tube by a vacuum pump, and the tube was sealed. The sealing nib is at the top of miniature tubes and very old tubes, and is covered by the aligning pin at the bottom of octal base tubes.

The silvery material spread over part of the inside of the tube is the getter. This coating (usually barium or aluminum) was vaporized inside the tube after sealing to further absorb the gas remaining in the envelope. Older tubes might have a somewhat discolored getter due to gas leakage. The getter cup that held the getter material, can usually be seen under the film. It is above the cage assembly on some tubes, and below it on others.

To open the tube, spread several layers of newspaper on a flat surface. Use goggles and gloves to prevent injury. With a triangular file, make a small scratch near the bottom. Wrap the tube with an old cloth, hold the tube with the scratch up on the table, and tap the tube with pliers or the file until it breaks. Unwrap the broken tube carefully, and examine the pieces. The getter film will begin to change as soon as it is exposed to air. In a few minutes it will be a white, powdery coating of barium oxide.

Protruding from the bottom of the cage assembly are the lead wires to the pins. Identify the filament leads (there are 2 or 3) as very fine wires with a white ceramic coating. Cut the other wires with diagonal cutters, but leave the filament leads intact. Separate the cage from the base, and slide out the filament.

The tube components in the cage are held in alignment with each other by the mica washers at the top and bottom of the cage. The mica also holds the cage in place inside the envelope.

To separate the components, examine the ends that protrude through the mica washer, and decide what to do before the mica can be pulled off the ends. It may be necessary to twist, cut, or bend these parts in order to disassemble the cage. When you have completed this operation, place the components on a clean piece of paper and examine them one at a time.

Mica was chosen as spacer material for its high strength, high electrical resistance, and the fact that it can withstand high temperatures. Mica consists of a complex compound of potassium, aluminum,

silicon, and oxygen in crystal form. Mica crystals have very weak bonds between the planes and so it can be split into thin sheets. Try it!

The small metal cylinder with a white coating is the cathode. It is heated from inside by the filament. At operating temperature electrons are "boiled off." The coating greatly increases the number of electrons emitted from the surface. When you wait for your TV to warm up, you are waiting for the cathode to warm up to an efficient emitting temperature.

The ladder-like arrangement of two parallel wires wound with very fine wire is called the grid. The electrons that were boiled off the cathode must pass through this grid. Because of this, the current in the tube is very sensitive to the field around the grid.

The dark cylinder that formed the outside of the cage is the plate. In an actual circuit, the plate is given a positive voltage relative to the cathode in order to attract the electrons emitted by the cathode. The electrons strike the plate and most give up their kinetic energy to the plate. The plate is a dark color in order to help dissipate this energy. Often, the coating is a layer of carbon, which can be rubbed off with your finger.

It is interesting to open different kinds of tubes and see how they differ. Some tubes have more than one cage in the envelope, multiple grids, or beam-confining plates.

(Adapted from "Looking Inside a Vacuum Tube," Chemistry, Sept. 1964.)

ACTIVITY A recorded research report

Make a tape recording, to play before your class, about some event in the history of science. Special effects like several different voices, background music and sound effects can make your presentation more interesting.

Your presentation may be in the form of an interview, a dialogue, a mock telephone conversation, or a dramatization (such as the "You Are There" series). You might also choose to show pictures, drawings, charts, or movies and key them to your report. You should check several sources in your school library to be sure you represent the facts of the event correctly. Use your imagination!

Some examples of events that would make good tape reports:

First trans-Atlantic radio broadcast (Marconi)

Manned space flight (Alan Shepard)

Underwater exploration (Boebe, Costau)

First heavier-than-air flight (Wright brothers)

First atomic pile (Fermi)

Discovery of astronomical objects (e.g. rings of Saturn, Pluto, first asteroid, etc.

ACTIVITY Bell Telephone science kits

Bell Telephone Laboratories have produced several kits related to topics in Unit 4. Your local Bell Telephone office may be able to provide a limited number of them for you free. A brief description follows.

"Crystals and Light" includes materials to assemble a simple microscope, polarizing filters, sample crystals, a book of experiments, and a more comprehensive book about crystals.

"Energy From the Sun" contains raw materials and instructions for making your own solar cell, experiments for determining solar cell characteristics, and details for building a light-powered pendulum, a light-commutated motor and a radio receiver.

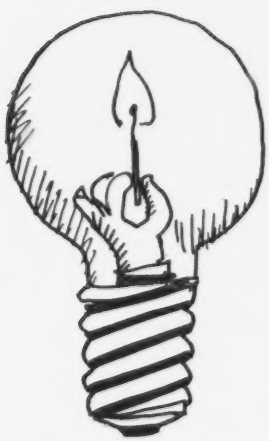
"Speech Synthesis" enables you to assemble a simple battery-powered circuit to artificially produce the vowel sounds. A booklet describes similarities between the circuit and human voice production, and discusses early attempts to create artificial voice machines.

"From Sun to Sound" contains a ready-made solar cell, a booklet and materials for building a solar-powered radio.

ACTIVITY Good reading

Several good paperbacks in the Science Study Series are relevant to Unit 4. The Physics of Television, by Donald G. Fink and David M. Lutyens; Waves and Messages by John R. Pierce; Quantum Electronics by John R. Pierce; Electrons and Waves by John R. Pierce; Computers and the Human Mind, by Donald G. Fink. See also "Telephone Switching," Scientific American, July, 1962, and the Unit 4 Project Physics Reader.

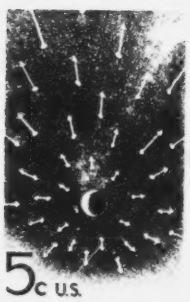
Confusion of wires due to development of electrical communications, Broadway and John Street, New York in 1890. (Courtesy of American Telephone and Telegraph Company)



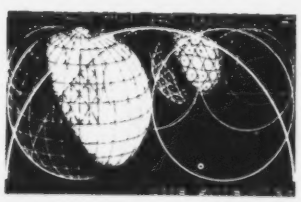
Science and the Artist

The Story Behind the New Science Stamp

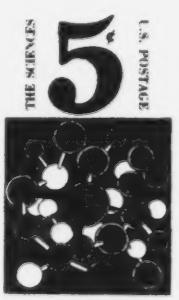
Albers



Bayer



Fuller



Frasconi

Thompson

The sciences and the arts are sometimes thought of as two distinct cultures with a yawning gulf between. Perhaps to help bridge that gulf, the Post Office Department held an unprecedented competition last year among five artists for the design of a postage stamp honoring the sciences.

The winning stamp, issued on October 14, commemorates the 100th anniversary of the National Academy of Sciences (NAS). This agency was established during the Civil War with the objective that it "shall, whenever called upon by any department of government, investigate, experiment, and report upon any subject of science or of art."

To celebrate the NAS anniversary, the late President Kennedy addressed the members of the academy and their distinguished guests from foreign scientific societies. After emphasizing present public recognition of the importance of pure science, the President pointed out how the discoveries of science are forcing the nations to cooperate:

"Every time you scientists make a major invention, we politicians have to invent a new institution to cope with it—and almost invariably these days it must be an international institution."

As examples of these international institutions, he cited the International Atomic Energy Agency, the treaty opening Antarctica to world scientific research (CHEMISTRY, Dec. 1963, p. 20), and the Intergovernmental Oceanographic Commission.

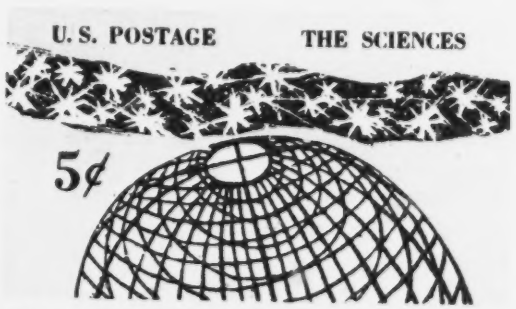
In the scientific sessions marking the anniversary, the latest views of man and matter and their evolution were discussed, as well as the problem of financing future researches—the proper allocation of limited funds to space research and medicine, the biological and the physical sciences.

The stamp competition was initiated by the National Gallery of Art, Washington, D.C. A jury of three distinguished art specialists invited five American artists to submit designs. The artists were chosen for their "demonstrated appropriateness to work on the theme of science." They were Josef Albers, Herbert Bayer, Antonio Frasconi, Buckminster Fuller, and Bradbury Thompson.

Albers and Bayer both taught at the Bauhaus (Germany), a pioneering design center that welded modern industrial know-how with the insights of modern art. (The Bauhaus is probably best known for its development of tubular steel furniture). Albers has recently published what promises to be the definitive work on color—"Interaction of Color" (Yale University Press). Bayer is an architect as well as artist; he has designed several of the buildings for the Institute of Humanistic Studies in Aspen, Col. Buckminster Fuller, engineer, designer, writer, and inventor, is the creator of the geodesic dome, the Dymaxion three-wheeled car, and Dymaxion map projection. Frasconi, born in Uruguay, is particularly known for his woodcuts; he won the 1960 Grand Prix Award at the Venice Film Festival for his film "The Neighboring Shore." Bradbury Thompson is the designer for a number of publications including *Art News*.

Ten of the designs submitted by the artists are shown here. The Citizen's Stamp Advisory Committee chose four of the designs from which former Postmaster General J. Edward Day chose the winner. The winning design by Frasconi, depicts a stylized representation of the world, above which is spread the sky luminescent with stars.

Which design do you feel most effectively represents the spirit and character of science, and why?



The winning design by Antonio Frasconi. The stamp was printed in light blue and black.

Film Loop 41 Standing Electromagnetic Waves

The phenomenon of standing waves is, of course, not confined to mechanical waves such as are shown in Loop 39 (Standing Waves on a String) and Loop 40 (Standing Waves in a Gas). The essential feature is to have a reflector at the proper distance from a source so that two oppositely-moving waves interfere with each other. A node is a point of destructive interference where the resultant disturbance is always zero; an antinode is a point of constructive interference where a maximum disturbance occurs. In this loop these ideas are applied to electromagnetic waves generated by a radio transmitter.

The specially-built transmitter operates at a frequency of 435×10^6 cycles/sec (435 megacycles/sec). Since all electromagnetic waves travel at the speed of light, the wavelength is $\lambda = c/f = (3 \times 10^8$ m/sec)/435×10^6 cycles/sec) = 0.69 m = 69 cm. To make a demonstration possible, these waves must be radiated, and they must be received. Both processes make use of standing waves. The output of the oscillator passes through a power-indicating meter, then to an antenna which consists of two rods each $\frac{1}{4}\lambda$ long as shown in Fig. 1. There is a current antinode (A) at the central feed point; electrons are flowing back and forth here. There are current nodes (N) at each end of the antenna, for here electrons have no place to go and the current must be zero. As in all standing waves, the distance from node to node is $\frac{1}{2}\lambda$, so the total length of the transmitting "dipole" antenna is $\frac{1}{2}\lambda$, or 34.5 cm.

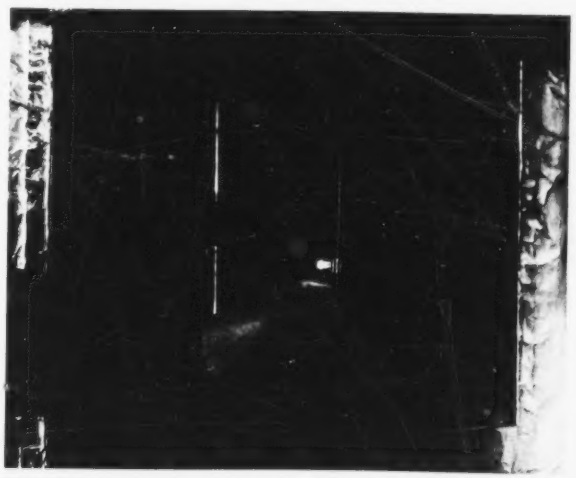


Fig. 2

The receiving antenna is also $\frac{1}{2}\lambda$ long (Fig. 2). It consists simply of a flashlight bulb connected between two stiff wires each $\frac{1}{4}\lambda$ long. If the electric field of the incoming wave is parallel to the receiving antenna, electrons in the wire experience a force tending to drive them back and forth through the bulb. The brightness of the bulb indicates the in-

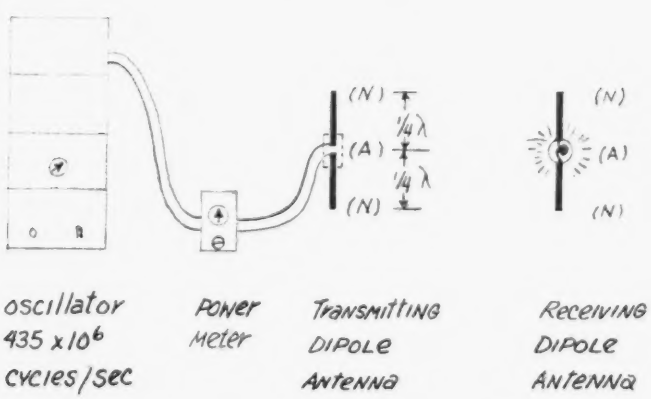


Fig. 1

tensity of the electromagnetic wave at the location of the antenna.

A long rectangular aluminum cavity, open on the side toward the camera, confines the waves to provide sufficient intensity for the demonstration.

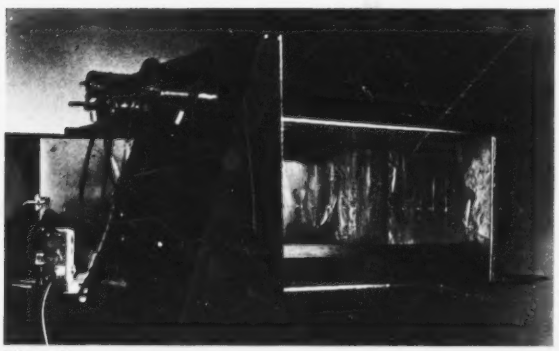


Fig. 3

1. The first sequence shows how the wave's intensity depends on the distance of a hand-held receiving antenna from the transmitting antenna. The meter near the transmitting dipole shows that the radiated power remains constant at about 20 watts (i.e., 20 joules/sec). Does the received intensity decrease steadily as the distance increases? Polarization is detected by rotating the receiving dipole antenna. Since the radiation is emitted with its electric vector polarized vertically, the response falls to zero when the receiving antenna is horizontal.

2. Standing waves are set up when a metal reflector is inserted at the end of the cavity opposite the source. The reflector can't be placed just anywhere; it must be at a node, hence the distance from source to reflector must be an integral number of half-wavelengths plus $\frac{1}{4}\lambda$. In other words, the cavity length is "tuned" to the wavelength. In the tuned cavity, the presence of nodes and antinodes is shown by moving a receiving antenna back and forth. Then a row of vertical receiving antennas is placed in the cavity, and the nodes and antinodes are shown by the pattern of brilliance of the lamp bulbs. Notice that the position of any node or antinode remains fixed; as the row of bulbs is moved back and forth first one bulb, then another, is glowing when it moves through the antinode.

3. Standing waves compared. Three types of standing waves are shown in one composite scene. All have the same wavelength, so the distance between nodes ($\frac{1}{2}\lambda$) is the same. Notice the similarity between the methods used to produce these patterns. In each case a source is at the left (tuning fork, loudspeaker, or dipole antenna); and a reflector is at the right (support for string, wooden piston, or sheet aluminum mirror). The wavelengths are the same, but the frequencies are not at all similar: they are 72 vib/sec for the string, 505 vib/sec for the gas, and 435×10^6 vib/sec for the electromagnetic waves. What can you conclude about the speeds of these three kinds of wave?

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Acknowledgments

Chapter Fourteen

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Chapter Sixteen

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